THE UNIVERSITY OF QUEENSLAND

AUSTRALIA

Integrated Modelling of Residential Water-Related Energy

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A thesis submitted for the degree of Doctor of Philosophy at

The University of Queensland in 2018

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Abstract

Around the world, urban demand for resources is increasing over time. In Australia, 90% of the population resides in cities, which are growing in both population and housing density. These factors place greater demands on water and energy, and associated greenhouse gas (GHG) emissions. Water use, energy use and GHGs are strongly interconnected, and thus actions to reduce water or energy consumption can have unintended consequences. Consequently, reducing water use without increasing energy use and GHGs as well as reducing energy use without increasing water use is important. One key area where this can be achieved is in the reduction of water-related energy (WRE) use.

WRE consumption occurs in two distinct sectors: the water sector through water supply and sewage collection services, and the residential sector through water end uses. WRE use of both utilities and end users are interconnected through infrastructure, environment, technology, behaviour, and policies. WRE use of water supply (10%) and sewage collections services (10%) are both within the control of utilities, however, the most WRE intensive component of the residential urban water cycle is residential end use (80%), which is largely outside the control of water utilities. This thesis used a systems approach to WRE modelling, across the water utility and residential sector interface, to investigate opportunities for whole-of-system reduction in resource consumption.

Firstly, this study investigated an interaction between the infrastructure and the environment through the cold water temperature (CWT) variability impact on household WRE. The spatiotemporal variability in CWT was determined using 5760 measurements from 1255 sampling locations across Yarra Valley Water, Melbourne, Australia. The monthly CWT varied across the 4000 km^2 study site from 12-28°C during summer and 9-15°C during winter. Spatial clusters of hot spots and cold spots were observed. Variation in CWT was calculated to affect annual household WRE demand by -17 to +19%. Variability in results demonstrated the difference in household WRE demand in hot spots, cold spots, and neutral zones.

Monthly mean CWTs for the study site diverged from hot water system (HWS) energy consumption guidelines by -21 to +47%. The CWT variability impact on household water heating varied up to three times the energy used by the water utility for water supply and sewage disposal services in this region. Results demonstrated the importance of modelling interactions between infrastructure and the environment. Quantifying the variability of CWT increased the accuracy of predicting regional WRE demand and HWS energy consumption.

Secondly, this study investigated how technology and behaviour influenced resource consumption at regional scales. This objective explored how the interactions between household composition, HWS type, shower use, and clothes washer use affected regional resource consumption in Reservoir, Melbourne, Australia. The regional ResWE model of water, WRE and GHGs, was up-scaled from a previously established household model using local water authority information and census data to capture end use variability between individual households. In total, 320 household types were used to characterise end use variability.

Shower systems were found to be the largest lever for reducing resources. Changes in shower technology and behaviour together were predicted to generate annual water reduction of 27% WRE-electricity reduction of 15%, WRE-gas reduction of 48%, and WRE-GHG reduction of 28%. Clothes washing highlighted the importance of accounting for interactions between behaviour and technology to reduce regional resources i.e. 100% penetration of front loaders reduced regional water use but increased regional WRE and GHGs because front loaders used more energy than top loaders for a cold wash cycle and 70% of households used a cold wash cycle. Economies of scale was a factor in the household composition effect on resource consumption where larger occupancy households were the lowest consumers per capita. In contrast, smaller occupancy households were the highest consumers: 53% of the population lived in 73% of the household stock and consumed 59% of resources. Thus indicating, prediction models of either water or energy use need to consider projected changes in demographics to effectively capture changes in resource use. Overall, results demonstrated how household interactions between technology and behaviour significantly determined regional resource consumption.

Lastly, this study proposed a conceptual model which coupled the regional ResWE model of residential water-energy interactions to a geographical information system platform. The conceptual model proposes integration of information from top-down data (utility decisions) and bottom-up data (end user decisions) over a range of spatial and temporal scales. This enables the evaluation of the cumulative impacts of changes in factors that influence WRE use across infrastructure, environment, behaviour, technology and policy decisions.

Integrated WRE modelling demonstrated the significant difference between household and regional water-energy interactions. This result would not have been found through a linear scale-up of household results. In conclusion, implications of both household and regional water-energy interactions need to be accounted for in the formation of policies related to water, energy or GHGs.

Declaration by Author

This thesis *is composed of my original work, and contains* no material previously published or written by another person except where due reference has been made in the text. I have clearly stated the contribution by others to jointly-authored works that I have included in my thesis.

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Publications Included in this Thesis

Bors, J., O'Brien, K.R., Kenway, S.J., Lant, P.A., 2017. *Regional-Scale Variability of Cold Water Temperature: Implications for Household Water-Related Energy Demand*. Resources, Conservation & Recycling 124: p. 107-115. – incorporated as Chapter 3.

Submitted Manuscripts Included in this Thesis

No manuscripts submitted for publication.

Other Publications During Candidature

Peer reviewed journal articles:

1. **Bors, J.**, O'Brien, K.R., Kenway, S.J., Lant, P.A., 2017. *Regional-Scale Variability of Cold Water Temperature: Implications for Household Water-Related Energy Demand*. Resources, Conservation & Recycling 124: p. 107-115. – incorporated as Chapter 3.
2. Kenway, S., Binks, A., **Bors, J.**, Pamminger, F., Lant, P., Head B., Taimre, T., Grace, A., Fawcett, J., Johnson, S., Yeung, J., Scheidegger, R., Badder, H.P., 2014. *Understanding and managing water-related energy use in Australian households: preliminary results of a research project being carried out by The University of Queensland and the Smart Water Fund.* Water. 41(2): p. 184-188.

Conference articles:

3. **Bors, J.,** Kenway, S., Lant, P., and Pamminger, F., 2014. *Temperature Variability in the Melbourne Water Network and the Impact on Residential Energy Use*. In Water, Energy and Climate Conference 2014: Solutions for Future Water Security, edited by International Water Association. Mexico City, Mexico: International Water Association.
4. Kenway, S.J., Binks, A., **Bors, J.**, Pamminger, F., Head, B., Lant, P., Taimre, T., Scheidegger, R., Bader, H.P., 2016. *Quantifying Water-Energy Linkages Opens New Pathways for Efficiency*. In Proceedings of OzWater '16, Australian Water Association, Melbourne.

Research group report:

5. Grace, A., Taimre, T., Kenway, S., and **Bors, J.,** 2014. *Cold Water Temperature in Melbourne 1994-2013, preliminary statistical analysis.* In Water-Energy-Carbon Links in Households and Cities: A New Paradigm, Water-Energy-Carbon Group, The University of Queensland.

Contributions by Others to the Thesis

No contributions by others.

Statement of Parts of the Thesis Submitted to Qualify for the Award of Another Degree

No works submitted towards another degree have been included in this thesis.

Research Involving Human or Animal Subjects

No animal or human subjects were involved in this research.

Acknowledgements

Firstly, thank you to A/Prof Steven Kenway for your support in fostering new and old industry connections, your exemplary research presentation skills and your relentless enthusiasm for promoting project outcomes and work collaborations. This thesis topic could not have been possible without Steven's early work. Secondly, thank you to Prof Paul Lant for consistently bringing the big picture into focus early on in the PhD, and the fact that you can always be counted on to engage in a lively debate on any topic at any time. I would also like to extend my thanks to Dr Brian McIntosh and Dr Cara Beal for your astute observations and invaluable feedback during each milestone. A deep felt thank you goes to A/Prof Kate O'Brien for your extraordinary higher order reasoning skills and emotional intelligence, a rarity amongst academics. You offered technical guidance and insightful encouragement through every step of my PhD journey.

On a more practical note, this thesis would also not have been possible without data support from key stakeholders. I would like to express my appreciation to: Yarra Valley Water Ltd, APA Group and Jemena, for the data they made available for this study. I am particularly grateful to Francis Pamminger at Yarra Valley Water and Keith Lenghaus at APA Group for their commitment to building research-industry partnerships. I would also like to thank Darebin City Council, Sustainability Victoria, Northern Alliance for Greenhouse Action, Moreland Energy Foundation, Melbourne Water, City West Water, South East Water and Eawag.

On a more personal note, I would like to express my appreciation for the unconditional support from my PhD coffee group, Miheka Patel, Miriam Peces Gomez and Lizanne Obersky, you've all been there for me through my triumphs and my woes. Your warmth, understanding, and good humour during our coffee chats have been a lifeline more important to me than coffee or chocolate! A special thank you to my mother, Slavica Bors, there are no words to express my gratitude for your unwavering belief in me, and the incredible role model you've always been. You've supported me in stepping outside the box of our cultural traditions and stepping into the strength of who I choose to be, thank you for your courage. To my extended family, a heartfelt apology for spending so much time away from you all, I honestly didn't know the PhD would take so much of me. Lastly, to my son Jashan BV, you are the reason I have always strived to be the best version of me, I wouldn't have got this far without you. I hold a deep and abiding gratitude for knowing you.

Financial Support

This research was supported by an Australian Government Research Training Program Scholarship. This research was also supported by the Smart Water Fund (project 9TR1-001), and the Australian Research Councils' Linkage Projects funding scheme (project LP120200745).

Keywords

residential water-energy nexus, urban water system, water utility, end use, material flow analysis, spatial statistics

Australian and New Zealand Standard Research Classifications (ANZSRC)

ANZSRC code: 090702, Environmental Engineering Modelling, 60%
ANZSRC code: 160404, Urban and Regional Studies (excl. Planning), 30%
ANZSRC code: 090903, Geospatial Information Systems, 10%

Fields of Research (FoR) Classification

FoR code: 0907, Environmental Engineering, 60%
FoR code: 1604, Human Geography, 30%
FoR code: 0909, Geomatic Engineering, 10%

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List of Abbreviations

ABS	**A**ustralian **B**ureau of **S**tatistics
AS/NZS	**A**ustralian **S**tandard/**N**ew **Z**ealand **S**tandard
BOM	**B**ureau **O**f **M**eteorology
CW	**C**lothes **W**ashing
CWT	**C**old **W**ater **T**emperature
EHWS	**E**lectric **H**ot **W**ater **S**ystem
Elec-S	**Elec**tric hot water system - **S**torage
GHG	**G**reen**H**ouse **G**as
GHWS	**G**as **H**ot **W**ater **S**ystem
Gas-C	**Gas** hot water system - **C**ontinuous
Gas-S	**Gas** hot water system - **S**torage
GIS	**G**eographic **I**nformation **S**ystem
H1	**H**ousehold type **1** of 16 shower use & clothes washing variations
HC	**H**ousehold **C**omposition
HT-1	**H**ousehold **T**ype **- 1** of 320 household types capturing regional variability
HWS	**H**ot **W**ater **S**ystem
LCA	**L**ife **C**ycle **A**nalysis
MMFA	**M**athematical **M**aterial **F**low **A**nalysis
MRIO	**M**ulti-**R**egion **I**nput-**O**utput
P1	**P**arameter **1** of 145 input parameters for the ResWE model
ResWE	**Res**idential **W**ater and **E**nergy model
RO	**R**esearch **O**bjective
RQ	**R**esearch **Q**uestion
S1	**S**cenario **1** of 7 scenarios
SA1	**S**tatistical **A**rea level **1**
SHWS	**S**olar **H**ot **W**ater **S**ystem
Sol-E	**Sol**ar hot water system - **E**lectric booster
Sol-G	**Sol**ar hot water system - **G**as booster
SU	**S**hower **U**se
UHI	**U**rban **H**eat **I**sland
WRE	**W**ater-**R**elated **E**nergy
WRE-elec	**W**ater-**R**elated **E**nergy – **electricity**
WRE-electricity	**W**ater-**R**elated **E**nergy – **electricity**

WRE-gas	**W**ater-**R**elated **E**nergy - **gas**
WRE-GHG	**W**ater-**R**elated **E**nergy - **G**reen**H**ouse **G**as
YVW	**Y**arra **V**alley **W**ater

Units

%	percent
Δ%	change in percent
°C	degrees Celsius
°F	degrees Fahrenheit
$gCO_{2\text{-}e}$/MJ	grams of carbon dioxide equivalent per megajoule
$kgCO_{2\text{-}e}$/MJ	kilograms of carbon dioxide equivalent per megajoule
$kgCO_{2\text{-}e}$/p.d	kilograms of carbo dioxide equivalent per person per day
GL/decade	Gigalitres per decade
GL/yr	Gigalitres per year
GJ/yr	Gigajoules per year
GWh/decade	Gigawatt hours per decade
GWh/m	Gigawatt hours per month
GWh/yr	Gigawatt hours per year
km	kilometres
$ktCO_{2\text{-}e}$/yr	kilotonnes of carbon dioxide equivalent per year
kWh	kilowatt hours
kWh/d	kilowatt hours per day
kWh/hh.d	kilowatt hours per household per day
kWh/hh.m	kilowatt hours per household per month
ΔkWh/hh.m	change in kilowatt hours per household per month
kWh/hh.yr	kilowatt hours per household per year
kWh/MG	kilowatt hours per mega gallon
kWh/ML	kilowatt hours per megalitre
kWh/p.d	kilowatt hours per person per day
L	Litres
L/d	Litres per day
L/min	Litres per minute
m	metres
m/s	metres per second
m^2	metres squared

min	minutes
min/d	minutes per day
min/decade	minutes per decade
min/yr	minutes per year
mm	millimetres
ML/decade	Megalitres per decade
ML/m	Megalitres per month
MWh/decade	Megawatt hours per decade
MWh/m	Megawatt hour per month
W	Watts
$W/m^2°K$	Watts per metre squared kelvin
wk^{-1}	per week

Chapter 1. Introduction

1.1. Background

Studies on the changing metabolism of cities revealed that urban demands for resources is increasing over time rather than decreasing [1-3]. This is a significant issue as the ecological footprint of the world's population already exceeds global biocapacity [1] indicating that city scale changes to resource use could have far reaching implications [4]. The challenge lies in designing sustainable cities that reduce water [5-7], energy and carbon flows [8-10]. Population growth and the outward spreading of urban development from city geographic centres is on the rise [8, 11, 12]. These factors place greater demands on water and energy [13-17]. In Australia, 90% of the population as of 2010, resides in urban environments [18, 19] which is still growing in number of residents and housing density. For example, the '*Victoria in Future (VIF)'* report predicted that from 2011-2031 an additional 2.2 million people will live in Melbourne alone, and an additional 900,000 new households will also have been built [20]. Conserving water use, energy consumption and greenhouse gas (GHG) emissions in cities amidst a growing population and the spread of urban development is the key to a sustainable future.

Water use, energy consumption and GHG emissions are strongly interconnected [21-23]. Water systems use energy, energy systems use water, and both energy and water systems contribute to GHG emissions [15, 22, 24]. Managing water or energy resources without accounting for these connections can lead to unexpected costs and risks [21, 25-27]. For instance, installing new climate independent sources of water has increased energy consumption in the Australian water sector [21, 28, 29] and consequently increased costs for utilities and consumers [19, 26, 30]. Despite these interactions, energy use is not always considered in water resource management [21, 31, 32]. Integrated water and energy management (i.e. such as water-related energy management) may present opportunities to improving water and energy use [13, 33-38] without problem shifting between water, energy and GHG emissions [39-43].

Water-related energy (WRE) consumption occurs in two distinct arenas: water utilities and end use. Water utilities are accountable for the energy use associated with water supply, and wastewater treatment services [29, 43, 44] (Figure 1-1). End users are accountable for the energy use associated with water use [2, 45, 46] (Figure 1-1). WRE consumption of both utilities and end users are interconnected through water infrastructure design, climate impacts, water appliance technology, end use behaviour, and policies. Knowledge of these interconnections can help identify and devise options to reduce resource use, minimise costs, and improve infrastructure design [4, 47]. For example, urban water demand management programs reduce water use which can result in reduced WRE consumption (utility and end user) [2, 48-51]. Therefore, understanding end uses (appliance technology and behaviour) that influence peak demand is important for infrastructure design improvements [50-55] for both water and energy utilities. More importantly, residential WRE consumption will depend on decisions made at utility and end user scales.

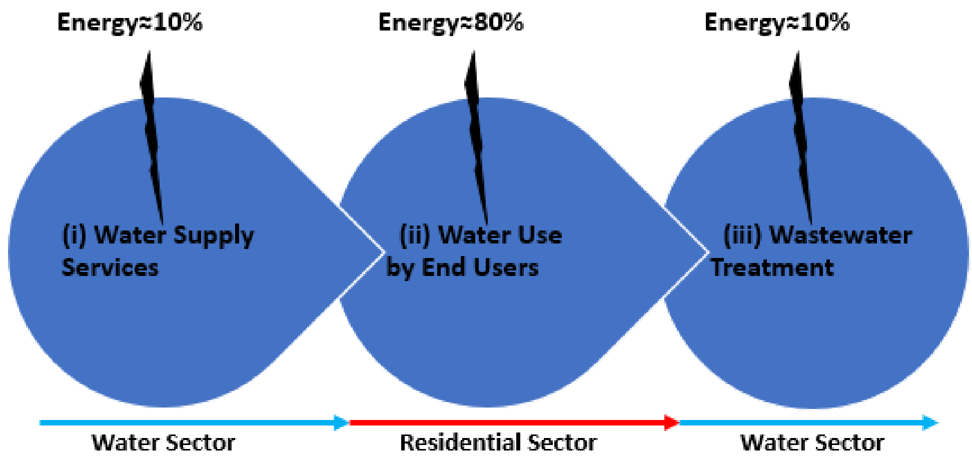

Figure 1-1: Cross-sectoral focus to reduce energy use in the urban water cycle

WRE consumption matters, because higher energy demand in the water sector will translate into increased energy costs and GHG emissions [56]. The most energy intensive component of the urban water cycle is residential end use [38, 46, 49, 57-63] accounting for at least 80% of WRE use in the residential urban water system [35, 64]. This poses many challenges. WRE use is often not considered by utilities [32, 35, 65] and end users [45, 58]. Even when it is considered, water utilities have little control over WRE use in the residential sector [58, 66]. Thus, widening the water utilities perspective on energy use to include WRE use in the residential sector presents opportunities to attain whole-of-system reduction in WRE [2, 39]. Moreover, substantial GHG emissions mitigation could be made by reducing residential WRE use [25, 35, 40, 44]. For example, increasing the uptake of solar hot water systems (SHWSs) in 80% of new dwellings and 20% of existing dwellings in Australia by 2045 would result in 140,000 GJ/yr energy savings across the water sector, and 30,000,000 GJ/yr energy savings across the residential sector, both achieved through residential WRE savings from SHWS use [67]. Minimising residential WRE is therefore important in reducing resource consumption in urban water systems.

There are two common approaches to quantifying residential WRE use: top-down and bottom-up modelling. Large scale residential WRE studies (top-down modelling) provide the big picture summary on resource use [23, 57]: how much is used, and at what stage of the water cycle. Small scale residential WRE studies (bottom-up modelling) tend to provide a detailed view of household water-energy interactions [68, 69] but not at a scale of analysis that could strongly inform government or utility decision making. Neither approach effectively evaluates large scale impacts of changes in factors that influence residential WRE use, because residential water use, associated energy and GHGs are driven by the combined effects of infrastructure design [60, 70], environmental influences [71-73], water appliance technology [48, 74-76], end use behaviour [72, 77-79], and policies [26, 45, 64, 80]. Consequently, a novel approach to quantifying residential WRE use to address limitations of current methods is needed. Moreover, there is a need for new tools to simultaneously evaluate large scale impacts of changes to factors that influence residential WRE use.

In light of the challenges and research needs identified, this PhD seeks to investigate WRE connections across the utility and residential boundary interface of the urban water cycle to identify residential WRE reduction opportunities. In particular, this thesis explores the combined influence of infrastructure, environmental conditions, technology and behaviour on urban water systems.

1.2. Research Aim and Objectives

The aim of this research is to investigate how infrastructure, environmental conditions, technology and behaviour affect WRE use across the utility and residential boundary interface, in order to identify WRE reduction opportunities. Three different modelling approaches were used: (i) spatial modelling of cold water temperature (CWT) is used to investigate how spatial and temporal variability in this parameter affects residential WRE use, (ii) a regional scale material flow analysis model is developed and applied to investigate how interactions between technology and behaviour affect regional water, WRE, and GHGs, and (iii) a conceptual model is used to illustrate how top-down and bottom-up data can be integrated to increase the information available to quantify WRE and manage urban water systems. An overview of the research objectives (RO) and research questions (RQ) used to achieve the aim of this work is presented in Figure 1-2.

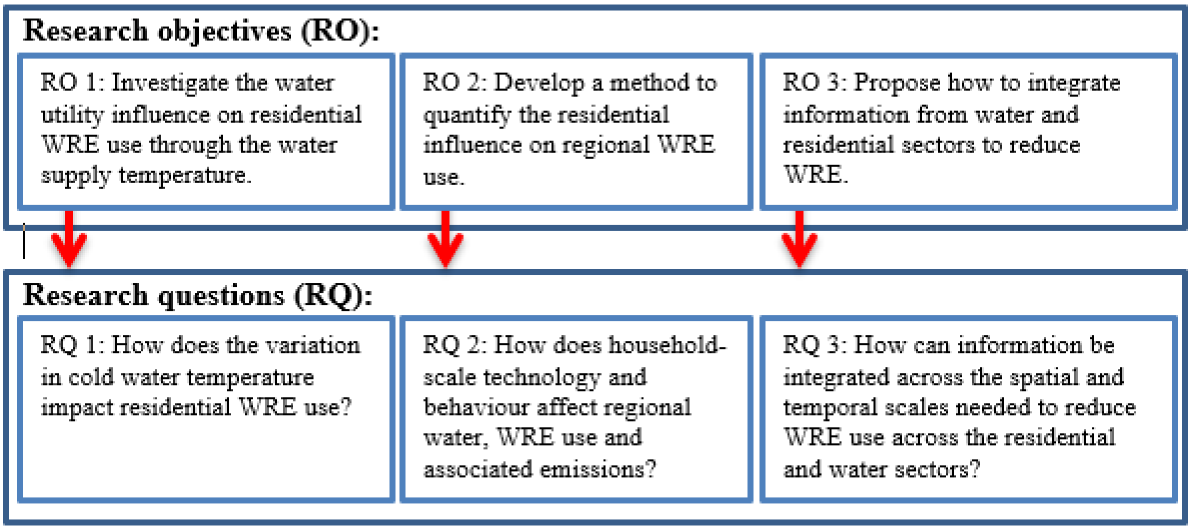

Figure 1-2: Research objectives and questions: steps to achieving research aim

RO 1: Investigate the water utility influence on residential WRE use through the water supply temperature.

CWT is a key driver for WRE consumption, because it affects the energy required to heat water. CWT can vary markedly within the domain of individual water utilities [73], driven by a combination of environmental conditions and water supply infrastructure [81]. However, the variability in CWT impact on household WRE use has not been quantified, and regional and seasonal variability in CWT are not accounted for in Australian Standards relating to hot water system (HWS) energy consumption. Thus, the objective of Chapter 3 is to characterize spatial and temporal variability in CWT and compare it with HWS energy consumption guidelines. This information is then used to quantify how regional scale changes in CWT, arising from interactions between water supply infrastructure and environmental conditions, can affect household WRE use at the household scale. Moreover, Chapter 3 answers the research question *'How does the variation in cold water temperature impact residential WRE use?'*

RO 2: Develop a method to quantify the residential influence on regional WRE use.

Regional scale consumption of water, WRE, and GHGs depend not only on the interconnections between water supply infrastructure and environmental conditions (explored in RO 1) but also on the interconnections between household scale technology, end use behaviour and policies. There is limited information on how technology and behaviour of individual households affect water and WRE consumption. As a result, regional scale predictions are often made by scaling-up detailed data from a very small sample of households or by using highly aggregated data to extract household averages. Neither of these methods capture the effects of household scale variability on regional scale consumption. Therefore, in Chapter 4, a regional scale WRE model is developed to capture end use variability between households and subsequently quantify the effect of household scale decisions on regional water, WRE and associated emissions. This is done in the context of water utility mandates as a guideline for scenario analysis. In particular, Chapter 4 answers the research question: *'How does household scale technology and behaviour affect regional water, WRE use and associated emissions?'*

RO 3: Propose how to integrate information from water utility and residential sectors to reduce WRE. WRE consumption of both utilities and end users are interconnected. More importantly, residential WRE use depends on decisions made at utility and end user scales. However, most WRE models do not have the capacity to model changes in WRE use across scales of decision making i.e., changes in water supply infrastructure, environmental conditions, water appliance technology, end use behaviour, and policies. Chapter 5 explores how to integrate utility scale decisions (top-down data) with end user decisions (bottom-up data) and directs future improvements in predicting WRE use for urban water system management. The work from Chapter 5 answers the research question: *'How can information be integrated across the spatial and temporal scales needed to reduce WRE use across the residential and water sectors?'*

1.3. Research Framework

The water-energy nexus denotes the conflicting interdependence of water and energy systems where water systems use energy, energy systems use water, and an increase in one resource often results in an increase in the other. The growing need to document water-energy interactions and efficiently co-manage water and energy is widely recognised [13, 15, 18, 24, 27]. Modelling and analysis of water-energy interactions are important to inform understanding and decision making in the management of water and energy resources [18, 36, 46, 77]. The water-energy nexus is influenced by a complex system of dynamically changing parts that include: (i) competing demands for water and energy, (ii) climate, (iii) technology options, (iv) demographics, (v) policies, (vi) economics, and (vii) land use [14]. Integrated modelling spanning these domains can improve the understanding of water-energy interactions whilst higher resolution spatial and temporal modelling can lead to emergent insights into developing resilient water-energy systems [14]. The focus of this study is the residential WRE aspect of the water-energy nexus framework.

1.4. Research Significance

This research investigates residential water-energy nexus issues from a multi-model perspective. This work contributes to expanding the water-energy nexus knowledge domain through a greater understanding of the structural, environmental, technological, and behavioural influences on residential WRE use. A household scale material flow analysis model of residential water-energy interactions was adapted for regional scale analysis to address a key limitation of current methods: an inability to evaluate the cumulative impacts of changes in factors that influence WRE consumption at larger scales. Another significant contribution of this work is the use of Geographic Information System (GIS) visualisation tools to effectively communicate complex water-energy nexus issues to stakeholders. A summary of the RO's, RQ's and contribution of research to practice and theory is presented in Table 1-1.

Table 1-1: Summary of the proposed objectives, methods and contribution to practice and theory

Research objective	Research question	Contribution
RO 1: Investigate the water utility influence on residential WRE use through the water supply temperature.	RQ 1: How does the variation in cold water temperature impact residential WRE use?	▪ Spatiotemporal maps of significantly warmer and cooler regions of CWT within a utility boundary. ▪ Estimated the impact of CWT variability on residential WRE use and identified an energy management opportunity.
RO 2: Develop a method to quantify the residential influence on regional WRE use.	RQ 2: How does household scale technology and behaviour affect regional water, WRE use and associated emissions?	▪ Developed and verified a detailed regional scale model of residential water-energy interactions inclusive of household heterogeneity and demographic groups. ▪ Quantified a base case scenario of regional scale residential WRE use. ▪ Estimated regional scale WRE savings under a variety of technology and behaviour change scenarios related to water utility mandates. ▪ Identified household and regional scale trade-offs and opportunities for water, WRE and GHG reductions. ▪ Provided direction on future model development and data collection.
RO 3: Propose how to integrate information from water and residential sectors to reduce WRE.	RQ 3: How can information be integrated across the spatial and temporal scales needed to reduce WRE use across the residential and water sectors?	▪ Developed a conceptual model for integrating top-down and bottom-up WRE information across water utility and household scales.

1.5. Thesis Structure

This thesis consists of six chapters and five appendices (Table 1-2). The first chapter provides an overview of the background, context and summary for this research. Chapter 2 presents the literature review behind the three major objectives. The remainder of the research is divided into three key stages.

The first stage of research, Chapter 3, evaluates the effect of water supply (i.e. cold water) temperature on WRE consumption. Spatiotemporal analysis of the variability of the CWT in the water distribution network (i.e. interaction between the environment and water infrastructure) demonstrates how utility scale infrastructure can influence household scale WRE use.

Table 1-2: Overall thesis structure and a description of each chapter's content and connectivity

Chapter ##	Title	Description
1	Introduction	The introduction establishes the context of this research and summarises the research aim, objectives, framework and significance.
2	Literature Review	The literature review summarizes the literature findings, identifies key knowledge gaps and formulates the research questions to be addressed in this project.
3	Regional Scale Variability of Cold Water Temperature: Implications for Household Water-Related Energy Demand	This chapter addresses RO 1 by: (i) quantifying the spatial and temporal variability of CWT, (ii) quantifying the potential impact of CWT variability on household WRE consumption, and (iii) highlights the broader implications for utilities and householders
4	Demographics, Technology, Behaviour and Environmental Variability Affect Regional Consumption of Water and Water-Related Energy	This chapter addresses RO 2 by: (i) developing a regional scale WRE model which incorporates environmental, technological and behavioural factors, (ii) verifying the model against empirical data, (iii) quantifying the impact of various technology, behaviour and demographic changes on water consumption, WRE consumption and emissions, then (iv) discussing the implications for utilities and householders.
5	Integrating Top-down and Bottom-up Information to Improve Prediction of Urban Water-Related Energy	This chapter addresses RO 3 by: (i) reviewing data challenges and limitations, and (ii) proposing a conceptual model for future WRE model development through the integration of key insights from this study.
6	Conclusions, Discussion and Recommendations	The conclusion summarises the key findings, applications, research project limitations and recommendations for future work.
Appendix A	Chapter 2: Support Information	This appendix presents the initial scope and summary of the literature reviewed to identify the research gaps.
Appendix B	Conference Paper	This appendix presents a copy of the conference paper that summarised the preliminary research findings presented in chapter 3.
Appendix C	Chapter 3 Support Information	This appendix provides the: (i) Chapter 3 modelling assumptions and simplifications, (ii) the mathematics behind the spatial statistics of the ArcGIS *Hot Spot Analysis* tool, and (iii) key *Hot Spot Analysis* results.
Appendix D	Chapter 4 Support Information	This appendix provides the: (i) Chapter 4 modelling assumptions and simplifications, (ii) details of the regional scale ResWE modelling design, (iii) procedures of key input parameter calculations, (iv) model verification data clean-up, and (v) key regional ResWE modelling results.
Appendix E	Chapter 5 Support Information	This appendix presents additional examples of the spatial and temporal scale misalignment of available data for the regional ResWE model.

A slightly modified version of Chapter 3 has been published in the '*Resources, Conservation & Recycling'* journal.

In the next stage of research, Chapter 4, a regional scale model of residential WRE use is developed through scaling-up a household scale WRE model. The model is parametrized using census data and local water utility reports, then verified with empirical data of water, electricity and gas use, and utility estimates of wastewater flow. This model demonstrates how household scale water end use decisions impact regional water use, associated energy and GHGs. The regional scale WRE model is used to evaluate water utility initiatives, such as the increased penetration of efficient shower heads and water efficient clothes washers. Scenarios of the current and the projected populations impact on regional water demand, WRE and GHGs were assessed.

The final stage of research, Chapter 5, integrates key research findings from the first and second stages in a conceptual model of a multi-scale modelling platform. The conceptual model is intended to improve residential WRE quantification through the integration of top-down and bottom-up data across spatial and temporal scales. Chapter 6 summarises the key conclusions, presents a discussion of the application of this research and includes further recommendations.

Chapter 2. Literature Review

This chapter forms the basis of the literature review identifying research gaps in the residential water-energy nexus and the subsequent development of the research objectives (RO's) and research questions (RQ's) that form the body of this work.

2.1. Preliminary Literature Review

Quantitative, qualitative and review papers on water, WRE and energy use of water supply systems and residential water end use were reviewed. Three categories were used to summarise the residential WRE literature gap of the water-energy nexus (Table 2-1): sector, scale and method. Firstly, reviewing studies from the utility sector identified that residential WRE was determined by water infrastructure decisions, demand management programs and environmental influences. Concurrently, residential sector studies identified that residential WRE was determined at the household scale through water appliance technology and end use behaviour decisions. Secondly, reviewing large scale studies provided information on resource use but little means of identifying levers of resource reduction whilst reviewing small scale studies provided detailed information on household water and energy interactions (e.g. levers of resource reduction) but weren't often at a relevant scale of analysis for government or utilities to formulate policies. Finally, a review of methods determined that resolving the information available between large scale (top-down modelling) and small scale (bottom-up modelling) studies could potentially be addressed by methods that contained a spatial and temporal component.

As a result of the preliminary literature review, the aim of this thesis was to establish the interconnections between residential WRE and supporting infrastructure through key drivers. Residential WRE drivers include: infrastructure (e.g. pipe size) [60, 70], environmental influences (e.g. ambient air temperature) [71-73], water appliance technology (e.g. shower head efficiency) [48, 74, 75], end use behaviour (e.g. shower duration) [72, 77, 78], and policies (e.g. demand management programs) [26, 45, 64].

Residential WRE use drivers were investigated through the thesis objectives. The first objective focused on evaluating the water utility influence on residential WRE use through the water infrastructure interaction with the environment resulting in cold water temperature (CWT) variability and the subsequent implications for household WRE use. The second objective focused on estimating the residential influence on regional resource consumption through household scale technology and behaviour choices as well as the impact of regional policies. The last objective focused on proposing how to integrate WRE information across water utility and residential sectors. This research led to an unexplored area of optimising resource consumption across the interface between urban water utility and residential sector boundaries. Further discussion on the preliminary literature review and a detailed categorisation of reviewed papers is presented in Appendix A.

Table 2-1: Preliminary review of residential water-energy interaction studies and research gaps

	Sector		Scale				Method				
Theme	**Residential**	**Utility**	**Building**	**Region**	**City**	**Larger than city**	**Top-down modelling**	**Spatiotemporal modelling**	**Bottom-up modelling**	**Review**	**Qualitative study**
Water	42	39	31	5	26	15	14	>5	32	14	18
WRE	53	29	23	**2**	20	13	15	**3**	22	9	5
Energy	30	22	18	5	16	10	13	>4	18	9	9

Reviewed Studies

• Rathnayaka et al. (2015)	• Agudelo-Vera et al. (2014)	• Bartos & Chester (2014)
• Elías-Maxil et al. (2014)	• Howells & Rogner (2014)	• Kenway et al. (2014)
• Martinez-Expineira et al. (2014)	• Nair et al. (2014)	• Rathnayaka et al. (2014)
• Stokes et al. (2014)	• US DOE (2014)	• Vieira et al. (2014)
• Binks et al. (2013)	• Brown et al. (2013)	• Chowdary et al. (2013)
• Chrysoulakis et al. (2013)	• Ferguson et al. (2013)	• Ferguson et al. (2013)
• Grant et al. (2013)	• Inamdar et al. (2013)	• Kenway et al. (2013)
• Laves et al. (2013)	• Lubega & Farid (2013)	• Makki et al. (2013)
• Miller et al. (2013)	• Nasiri et al. (2013)	• Nguyen et al. (2013)
• Novotny (2013)	• Siddiqi & de Weck (2013)	• Siddiqi et al. (2013)
• Stephan et al. (2013)	• Stokes et al. (2013)	• Willis et al. (2013)
• Zhou et al. (2013)	• Beal et al. (2012)	• Camci et al (2012)
• Carragher et al. (2012)	• Ferrari et al. (2012)	• Howard et al. (2012)
• Hussey & Pittock (2012)	• Ilha & Ribeiro (2012)	• Lee & Tansel (2012)
• Panagopoulos et al. (2012)	• Plappally et al. (2012)	• Sanders & Webber (2012)
• Stephan et al. (2012)	• Strengers & Maller (2012)	• Beal et al. (2011)
• Brazeau & Edwards (2011)	• Dominguez et al. (2011)	• Fuller & Crawford (2011)
• Goto et al. (2011)	• Hering et al. (2011)	• Kenway et al. (2011)
• Kenway et al. (2011)	• Lee et al. (2011)	• McMahon & Price (2011)
• Minne et al. (2011)	• Muthukumaran et al. (2011)	• Perrone et al. (2011)
• Proenca et al. (2011)	• Rothausen & Conway (2011)	• Scott (2011)
• Scott et al. (2011)	• Siddiqi & Anadon (2011)	• Stamminger (2011)
• Willis et al. (2011)	• Boyle et al. (2010)	• Conrad et al. (2010)
• Fidar et al. (2010)	• Pakula & Stamminger (2010)	• PMSEIC (2010)
• Shimoda et al. (2010)	• Wong et al. (2010)	• Flower (2009)
• Jorgensen et al. (2009)	• Leidl & Lubitz (2009)	• Retamal & Turner (2009)
• Stokes & Horvath (2009)	• Swan & Ugursal (2009)	• Goldstein et al. (2008)
• Burch & Christensen (2007)	• Hajkowicz & Collins (2007)	• Kennedy et al (2007)
• VandeWeghe & Kennedy (2007)	• Arpke & Hutzler (2006)	• Saliba & Gan (2006)
• Engel-Yan et al. (2005)	• Sahely et al. (2005)	• Crawford & Treloar (2004)
• Lundie et al (2004)	• Turner et al. (2004)	• Arbues et al. (2003)
• Cheng (2002)	• Herrmann et al. (1994)	• Ohnaka et al. (1994)

2.2. Water Utility Influence on Residential WRE

2.2.1. Water infrastructure and residential water heating

Understanding how the water infrastructure interacts with environmental influences and residential resource consumption is essential for developing sustainable infrastructure systems [27]. The need for detailed research to examine the connections between the urban form and overall energy use has been identified [82] along with the need for a greater understanding of the complexity of sustainable infrastructure development [11, 83]. Of particular interest, is that water management plays a key role in 10-20% of urban energy use, largely through indirect energy impacts which are considered outside the water utility boundary of responsibility [58]. From a water utility perspective, indirect energy impacts occur in a number of ways, for instance, energy for transporting alternative water sources such as rainwater tank pumps or residential water heating [2] which is the most energy intensive component of the urban water cycle [46, 59, 62, 72, 84, 85].

Residential water heating consumption accounts for at least 80% of total WRE in the urban water cycle [35, 64] but the connection between water infrastructure, management and residential water heating is poorly understood. In particular, CWT has a major impact on residential hot water system (HWS) energy use [68, 71, 86] as the cold water inlet (starting) temperature determines the energy required to produce the HWS outlet temperature set by the thermostat [87]. CWT is often considered a constant when evaluating HWS energy use, however, water infrastructure interactions with the environment (e.g. ambient air temperature) varies CWT values [81]. Thus, investigating how CWT varies across water infrastructure systems provides a way to quantify the water utility impact on household water heating.

2.2.2. CWT impact on household WRE

2.2.2.1. CWT in WRE modelling

The degree to which CWT varies across a water distribution network is not well documented. The temperature of municipal water supply can be location dependent and vary according to the temperature of the water source [7, 59, 80]. Models that predict or incorporate CWT as a component of WRE consumption either use one of the following methods: (i) empirical, or (ii) a derivation from air temperature data. An example of an empirical data application can be found in '*Energy Use in the Australian Residential Sector 1986-2020*' by Energy Efficient Strategies where monthly average CWT values were used to evaluate HWS energy consumption for a wide range of water heaters [88]. Climate based impacts of each water heating scenario were determined by using climate zone specific CWT values [88] outlined in Table 6 of AS/NZS 4234:2008 [89].

CWT derivations from ambient air temperature can be found in a number of studies in connection to hot WRE use. Lee [87] developed a simple algorithm for predicting the cold water inlet temperature for HWSs whilst Burch & Christensen [81] developed a sinusoidal function incorporating water infrastructure characteristics that predicts CWT from the main distribution pipe. Siddiqi and de Weck [90] calculated the energy demand of hot water use from the temperature difference between the hot water outlet temperature and the ambient air temperature. This approach assumes that ambient air temperature is a proxy for cold water inlet temperature and neglects water infrastructure influences such as pipe insulation. Wong et al. [91] developed an algorithm correlating the water supply pipe temperature for shower use to ambient outdoor air temperature and observed that water supply pipe temperature was consistently higher. Zlatanovic et al. [92] mathematically modelled the temporal change of water temperature inside pipes by solving the energy balance between the source water temperature and ambient air temperature using pipe characteristics and the physical properties of water and air. This study observed that the heat exchange between water and air through the pipe wall was the most dominant transfer process. This list of studies is not exhaustive but provides an overview of the accepted correlation between ambient air temperature, CWT and WRE consumption.

Burch and Christensen [81] found that CWT was influenced primarily by: (i) seasonal variation in source water temperature, (ii) water storage tank design, (iii) numerous storage tanks that fed the water infrastructure network, (iv) ground temperature, (v) feeder pipes exposed to surface temperature, and (vi) indoor pipes exposed to indoor ambient air temperature [81].

A key observation from this study is that CWT varies spatially and temporally along the water distribution network (±5°F) [81]. Considering the dynamic flows of the water supply network including the multiple points of temperature influence (Figure 2-1), it would be prudent to accept that CWT at the HWS inlet is not a constant temperature. This knowledge could yield significantly different calculation results from current HWS design standards. For instance, AS/NZS 1056.4:1997 *'Storage water heaters – Daily energy consumption calculations of electric types'* assumes a constant cold water temperature of 15°C in most calculation examples [93] and AS/NZS 4234:2008 *'Heated water systems – Calculation of energy consumption'* draws on average monthly, climate zone based CWT values for solar water heaters and heat pumps where Australia is broadly categorised into four climate zones [89]. Both standards rely on steady CWT values which neglect the CWT variability across the distribution network.

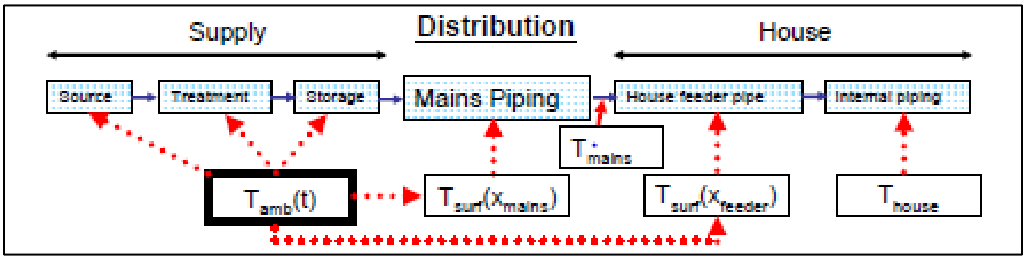

Figure 2-1: Ambient air temperature influence on water supply temperature (Tmains) from source of water, treatment and supply through the mains piping of the water sector to the residential sector through feeder pipes and internal piping of households; source: [81].

Regardless of the method used to predict CWT, there can be a significant variability in CWT along the distribution network which will in turn influence residential WRE consumption associated with hot water use. Influences on CWT include water infrastructure attributes (e.g. metal storage tanks and pipe location), and environmental attributes such as air temperature (e.g. ambient, surface and indoor), and ground temperature.

2.2.2.2. Implications of CWT variability on WRE

The indirect implications of water management on WRE have not been greatly considered [86] such as CWT which influences the energy consumption of all HWSs [2, 81]. However, preliminary results of the seven households studied in Kenway et al. [94] revealed that a change of approximately 2°C in water temperature led to an increase in 0.3-0.7 kWh/hh.d of energy use for the specified set of household characteristics. Subsequently, between 2% and 14% of total household WRE use was influenced by a 2°C change in CWT. These results, in conjunction with the water infrastructure influence on CWT (and resultant CWT variability) identified in Burch and Christensen [81] indicated that CWT significantly influences residential WRE use as an unforeseen outcome of water infrastructure interaction with the environment. Consequently, the significant effect of CWT variability on residential WRE use, and the lack of knowledge concerning the spatial and temporal variability of CWT, led to the first research objective (RO) and research question (RQ) of this thesis:

RO 1: Investigate the water utility influence on residential WRE use through the water supply temperature.

RQ 1: How does the variation in cold water temperature impact residential WRE use?

Investigating this research objective is intended to: (i) highlight an urban water management opportunity in reducing residential WRE through the CWT delivered to households, (ii) provide insights for improving engineering design guidelines of water supply infrastructure and HWSs, and (iii) assist in quantifying the impacts of regional scale variability of residential WRE use.

2.3. Residential Influence on WRE

There are numerous studies that quantify residential water and WRE associated with specific technologies and behaviours but few which quantify the cumulative impact of different technologies and end use behaviours at larger scales. Additionally, the four biggest determinants of residential water, WRE use and associated GHGs have been identified in previous studies as household composition [49, 50, 68, 95-98], HWS type [8, 60, 75, 80, 99-101], shower use [46, 80, 91, 98, 102-105], and clothes washing use [46, 48, 103, 106-108]. The basis of the second objective literature review included: (i) studies on the impacts of water appliance technologies and end use behaviours through the four biggest determinants of water, WRE use and associated GHGs, (ii) approaches to quantifying WRE, and the (iii) potential to reduce residential WRE and associated GHGs.

2.3.1. Key determinants of household WRE

2.3.1.1. Household composition

A key determinant for household resource consumption is the number of occupants [49, 50, 68, 95-98], adults, children and visitors. For example, Kenway et al. [68] estimated that a 10% increase in adult occupancy rates increased GHGs by 0.2 $kgCO_{2\text{-}e}$/hh.d whilst a 10% increase in child occupancy rates only increased GHGs by 0.1 $kgCO_{2\text{-}e}$/hh.d, half of the emissions produced by an adult visitor. However, water, WRE use and GHGs of an average household (with an average household composition and occupancy rate) is often scaled-up to evaluate regional WRE use. For example, Flower [63] used hypothetical households of three persons each to evaluate the performance of three HWS types at city scale. Realistically, household composition ranges from single occupancy dwellings to multi-family dwellings [20]. Consequently, evaluating resource use with averaged household data would ultimately increase the uncertainty in WRE results. Depending on local demographics, household averages could lead to either overestimation or an underestimation of regional resource use. Therefore, it is important to include the variability in household composition across regions, for greater certainty in regional resource consumption estimates.

2.3.1.2. HWS types

Determining the energy requirements of water end uses is considered complex [60]. Consequently, the energy consumption of residential HWSs is often used as a simplified method for quantifying residential WRE [60, 85, 99, 109, 110]. Moreover, a number of HWS types are used to quantify

WRE: electric and gas systems with storage, continuous gas systems, as well as electric, and gas-boosted solar systems [100]. Furthermore, scenario testing of different HWSs is often used to quantify potential reductions in residential WRE use [75, 99, 100, 109] to determine methods of promotion and adoption of ecologically efficient HWSs [109, 111-113]. However, this approach excludes other sources of WRE such as the mechanical energy of water appliances and/or water appliance technology upgrades. Additionally, emphasis has recently been placed on the significance of end use behaviour in quantifying WRE consumption [72, 77, 78]. There is therefore a limit to determining the key influences in residential WRE use by only quantifying the energy consumption of HWSs. A whole-of-system approach to quantifying residential WRE consumption of water end uses is recommended where water appliance technology and end use behaviour are modelled along with HWS type.

2.3.1.3. Shower use

A significant energy consuming water end use is shower use [46, 80, 91, 98, 102-105]. Shower head efficiency, duration and frequency of shower use determine the volume of water used [114-116] whereas the energy required for the water heating component denotes the energy consumption of shower use [103].

Studies show seasonal differences in shower water use [114, 117] which could reveal key influences for residential WRE. Rathnayaka et al. [117] observed the weather sensitivity of shower use even though results did not confirm whether there was an increase during summer vs winter due to opposing results from different regions. The study confirmed that average shower duration in winter was longer than in summer and proposed that people enjoyed long warm showers in cold weather as an explanation of the seasonal variation [117]. Even though shower duration was tested, shower temperature was not a measured variable therefore it is inconclusive whether there is a seasonal change in shower temperature. Furthermore, indoor ambient air temperature has been identified as a key influence in assessing personal thermal comfort levels which is strongly correlated to a person's choice of shower water temperature [118, 119]. Therefore, it could be theorized that space heating in bathrooms would influence a person's choice of shower water temperature. Moreover, lower shower temperatures and consequently lower energy consumption for showering, could be attributed to space heating already present in some homes during winter. Determinants of the seasonal differences in shower use and associated WRE consumption is inconclusive and indicates a need for further research.

2.3.1.4. Clothes washing use

Clothes washing is well known as a prominent energy consuming residential water end use [46, 48, 63, 68, 103, 106-108, 120], yet, there is still uncertainty around the trade-offs between water and energy consumption in washing machine types. It is unclear whether internally heated (single connection) clothes washers have a larger energy-intensity and associated GHGs than externally heated (dual connection) washing machines [2]. Kenway et al. [68] attributed 37% of water-related GHG emissions to clothes washing use and emphasized that replacing an externally heated clothes washer (connected to GHWS) with a water efficient clothes washer (single connection) would result in an increase in GHG emissions. This contradicts findings in Beal et al. [48] which noted water efficient clothes washers are less energy-intensive because they internally heat the exact amount of water needed for washing rather than drawing water from a HWS which uses additional energy to maintain a larger volume of hot water on standby. This idea is supported by the 2013 Wuppertal Institute report on *'What users can save with energy and water efficient washing machines'* [121]. Nevertheless, Beal et al. [48] demonstrated that clothes washers connected to instantaneous GHWSs have a larger energy-intensity for single connection compared to dual connection washers which contradicts the main findings of other HWSs studied but could support the observation from Kenway et al. [68]. The opposing conclusions in these studies indicate that further understanding of the trade-offs between water and energy consumption of clothes washer types with respect to fuel source is needed.

2.3.2. Residential WRE modelling

Currently, there are two major approaches for quantifying water-energy interactions: (i) top-down and (ii) bottom-up. Top-down modelling approach is typically applied in large scale studies, and relies on highly aggregated data [9], for example, data that represents the whole sector of interest [122] such as input-output models. Top-down studies provide the big picture summary on resource use but cannot be connected to key levers for mitigating WRE use such as the technological or behavioural aspects of end use activities. The bottom-up modelling approach is used in smaller scale studies. Examples of bottom-up data include partial sector input data and/or individual data derived from surveys and/or interviews [122] and/or end use meters. Bottom-up studies highlight the key factors controlling household water-energy interactions however, these studies do not often span a scale of analysis that could robustly inform management decisions such as the implementation of competing rebate schemes.

Key bottom-up WRE modelling studies have focused on quantifying WRE consumption for more than one water end use. WRE studies to date, have focused on the evaluation of energy savings and related GHGs. Fidar et al. [44] quantified energy use and related GHGs from changes in water appliance efficiency in households across England. Siddiqi & de Weck [90] evaluated energy requirements for buildings through changes in hot water usage fractions, pumping and source water (i.e. desalination, recycling etc.) for Masdar City, United Arab Emirates. Kenway et al. [68] developed a model quantifying water demand, energy demand, related GHGs and resource costs from changes in water appliance technology, end use behaviour, and environmental parameters, using data from a single household in Brisbane, Australia. Chini et al. [49] developed water and energy cost abatement curves to evaluate US residential water and energy savings from a range of appliance upgrades using data from an average single family. These studies can be difficult to use as a basis for policy formation due to the limited representation of household variability.

A more recent trend in bottom-up studies, water and energy data have been sourced from larger datasets to allow for household heterogeneity in WRE modelling. Beal et al. [48] evaluated energy savings and related GHGs from water savings through resource efficient household stock using empirical data from 252 households, Brisbane, Australia. Abdallah and Rosenberg [77] modelled water and energy use for US households through changes in water appliance efficiencies using disaggregated, national energy and water use data as well as probability distributions of water and energy use factors. Escriva-Bou et al. [80] developed a model quantifying water demand, energy demand, related GHGs and costs from changes in water heater technology, end use behaviour, and environmental parameters using probability distributions of data for 10 utilities in California. These studies have highlighted potential levers for mitigating WRE use and made progress in including household heterogeneity. The inclusion of household heterogeneity in WRE modelling is important for understanding how variability in household scale decisions can inform utility and/or government decisions related to water and WRE policy formation at larger spatial scales.

These studies highlight that modelling changes in residential WRE can be achieved through evaluating changes in: water appliance technology [44, 48, 49, 68, 69, 77, 80], end use behaviour [48, 68, 69, 77, 80], and environmental influences [68, 69, 77, 80, 90]. However, few studies have evaluated the cumulative impacts of changes in water appliance technology, end use behaviour and environmental conditions. Theoretically, the household ResWE model in Kenway et al. [68] is capable of quantifying the collective impacts in the key factors influencing residential water, WRE use and GHGs. Additionally, the household ResWE model is capable of being adapted to capture household heterogeneity for a regional scale application which has not yet been explored.

It's important to note that the most recent WRE studies have focused on evaluating water and energy end use meter data to classify real-time end use events [50, 54, 55, 123, 124]. A significantly larger number of households can be evaluated using this method compared to previous bottom-up WRE modelling studies. However, this WRE modelling approach is still in its infancy and considered computationally intensive with further need of method development. End use meter studies showcase potential applications for utilities, regulatory agencies and end users [54, 55, 123].

2.3.3. Reducing WRE and GHGs

Residential WRE has been identified as an opportunity for potential energy savings. Moreover, there has been an increasing focus on energy efficient water heating systems [99, 101] due to the large proportion of residential energy consumption contributed to water heating [34, 72]. Residential water heating in Australia accounts for 23% of residential energy use [125] where the residential sector consumes a 26% share of total net energy use [126]. Australia's residential water heating consumption is estimated to be seven times higher than the energy consumption of water utilities where a 15% reduction in residential WRE use (2006/2007 rates) could account for the total energy requirement of water utilities [58]. Despite the potential benefits of reducing WRE consumption, the relative proportion of residential water heating compared with total residential energy use could continue to increase rather than diminish due to advancements in building performance that reduce energy requirements for space heating. Consequently, this emphasizes the importance of transitioning to more energy-efficient water heating systems [8, 34, 48, 99, 101] and the need to further identify WRE savings opportunities.

The residential water heating contribution to residential energy use indicates WRE as one of the largest residential sources of GHG emissions and presents an opportunity to reduce GHGs. Coal-fired electricity and natural gas are the main sources of energy for the residential sector in Australia [100] which emitted 102 Mt $CO_{2\text{-eq}}$ in 2010. 24% of total residential GHG emissions in 2010 was attributed to water heating where 44% electric and 43% gas based water heaters dominated the sector [113]. Ferrari et al. [113] reviewed the predominant water heaters on the Australian market and found the largest share of emissions are produced from electric water heaters with more than 325 $gCO_{2\text{-eq}}$ per MJ of heat, followed by gas water heaters (83-138 $gCO_{2\text{-eq}}$ per MJ), solar electric water heaters (47-152 $gCO_{2\text{-eq}}$ per MJ), and the most ecologically efficient was found to be solar gas water heaters (11-62 $gCO_{2\text{-eq}}$ per MJ). The Melbourne residential sector primarily uses GHWSs therefore a switch to solar gas water heaters would reduce residential GHG emissions [13, 100]. Switching to ecologically efficient water heaters would greatly reduce residential GHG emissions and further supports the need to identify WRE savings opportunities.

Another means of reducing residential WRE and associated GHGs is through warm water conservation. For instance, replacing a standard shower head with an efficient shower head is a recommended strategy for reducing water use [98, 104, 127], WRE use [98, 102, 128], and GHGs [34]. However, Ohnaka et al. [129] verified that restricted-flow (i.e. efficient) shower heads led to an increase in preferred water temperature which would increase the WRE consumption and related GHGs of shower use. This could lead to a perverse outcome where an increase in water efficiency (i.e. reduced water use from installing an efficient shower head) could result in an increase in WRE use and emissions. Furthermore, the extensive work on identifying the most influential factors of shower use (e.g. temperature, duration, flowrate) conducted by Kenway et al. [98] emphasized that technological factors were far less influential than behavioural factors for both water and WRE use of shower systems. Thus, it is important to model changes in shower use technology and behaviour in WRE models.

In summary, it is proposed that the household ResWE model in Kenway et al. [68] be adapted for regional scale modelling of household scale changes in water appliance technology and behaviour. Additionally, the four key determinants of household WRE use (i.e. household composition, HWS type, shower use and clothes washing use) be used to capture household heterogeneity for a better understanding of regional resource use. Therefore, the second research objective and research question of this thesis is:

RO 2: Develop a method to quantify the residential influence on regional WRE use.

> ***RQ 2: How does household scale technology and behaviour affect regional water, WRE use and associated emissions?***

Investigating this objective is intended to provide: (i) a base case scenario of regional scale residential WRE use, and (ii) a means of identifying important levers to minimise regional water, WRE use and GHGs through implementable water appliance technologies and recommended changes in behaviour. The main outcome for this objective is to identify the trade-offs and opportunities to increase resource use efficiency and more accurately predict future demand for resources.

2.4. Integrating Water Utility and Residential WRE Data

To date, section 2.2 focused on water utility influence on residential WRE use. This section highlighted the connection between water infrastructure, the environment, and the resulting CWT variability impact on household WRE use important for WRE modelling. In particular, the importance of including large spatial scale parameter (i.e. utility water infrastructure zones) and large temporal scale parameter (i.e. seasonal changes in CWT) effects on household resource use. Section 2.3 focused on the household influence on residential WRE use. This section identified the interactions between water appliance technology and end use behaviour of the key determinants in household WRE use important for residential WRE modelling. This section also highlighted how household changes in technology or behaviour could impact regional WRE savings, moreover, the importance of including small spatial and temporal scale parameter (i.e. household level decisions) effects on regional resource use. Studies reviewed in sections 2.2 and 2.3 depend on WRE data inputs that are integral for WRE modelling, however, the data inputs are at different scales i.e. utility and household scale. This leads to the literature review for the final objective of this thesis: the need to integrate different spatial and temporal (i.e. spatiotemporal) scales of data inputs to incorporate WRE decisions from households to utilities, in WRE modelling.

The multilevel regression modelling is relatively new (as compared to other well-known and used methods) and has great potential for application in cases where multiple spatial and temporal scales are involved. Multilevel regression modelling has the ability to link geographical locations to descriptive features (data inputs) that vary across space and time [130]. The multilevel data inputs for improving WRE modelling can be described as: (i) individuals, to (ii) households, to (iii) regions, to (iv) water utilities. A distinguishing feature of multilevel regression modelling over traditional regression analysis techniques is the modelling of variations between groups [131] in other words, modelling of variations between groups at each of the nested levels described. For example, the multilevel data inputs for WRE modelling would include the variability of: (i) end use behaviour choices between individuals, (ii) water appliance technology choices between households, (iii) environmental conditions between regions, and (iv) policies between water utilities. Thus, multilevel regression modelling allows investigation of the interconnections between different spatiotemporal levels of descriptive features.

A key platform for spatiotemporal modelling of multilevel data inputs is Geographic Information Systems (GIS). In particular, multilevel data inputs can be stored in an ArcGIS platform which enables spatial statistical analysis such as multilevel regression analysis [132]. For this objective, spatiotemporal modelling of WRE through GIS studies is explored for integrating utility and household scale data inputs.

2.4.1. Spatiotemporal modelling of WRE

The spatial distribution of residential WRE consumption is complex. The spatial change in water and energy demands impacts supporting infrastructure. Additionally, residential WRE use varies in time as a response to peak water demands as well as seasonal changes in water end use which further impacts supporting infrastructure. Understanding the spatial and temporal distribution of residential WRE consumption in the context of supporting infrastructure is important in selecting appropriate resource conservation measures. GIS has previously been used as a tool for assessing urban metabolism with regard to building and supporting infrastructure in order to understand spatial and temporal changes in material accumulation [133]. This application indicates that spatiotemporal modelling in GIS could also be used to analyse residential WRE in the context of supporting infrastructure. Moreover, spatiotemporal modelling of residential WRE in a GIS framework could provide information on how to minimise residential WRE consumption across the interface between water and residential sectors due to its multi-scale modelling application.

The few studies that included WRE use, did not quantify the residential WRE of water end uses. Saliba and Gan [134] produced an energy density (kWh/ML) map to communicate the variation in the combined energy intensity of water supply and wastewater services. Similarly, Spang and Loge [135] produced energy density (kWh/MG) maps of water supply and sewage disposal services whilst Spang et al. [136] evaluated the potential upstream energy and GHG savings of water conservation. The importance of understanding infrastructure interactions to properly plan for sustainable cities was highlighted by Minne et al. [83]. This study proposed to build an agent based model for predicting social decision making and subsequent demand for urban infrastructure through the integration of water, energy, land use, transportation, material use, policy decisions and socio-economic data [83]. WRE input data of water supply and wastewater services (kWh/MG) was an averaged value for each city studied and the average value of residential energy use (kWh/p.d) did not include a breakdown for residential WRE [83]. The spatial distribution of urban building energy consumption was modelled in by Howard et al [137]. The residential WRE within this study was very coarsely modelled as a water heating fraction of annual energy consumed [137]. Even though residential WRE was not a key focus, this study provided insights into the dynamics of local energy use as a precursor to understanding how to remedy issues with current energy distribution infrastructure [137]. There were two key features: (i) multiple linear regression analysis was used to determine the predictors for energy consumption in buildings, and (ii) the map of spatially distributed energy use was used to identify opportunities for cost-effective reuse of waste heat streams [137]. All three studies demonstrated the value of using maps to communicate spatial and temporal changes to further support decision making at a relevant scale of analysis and highlighted the lack of detailed spatiotemporal modelling of residential WRE.

In summary, there are currently no residential WRE models that evaluate large, regional scale impacts of changes in water infrastructure, environmental influences, water appliance technology, end use behaviour, and policies. Additionally, the reviewed studies did not provide a method of quantifying residential WRE in the context of supporting infrastructure systems. However, spatiotemporal modelling of resource consumption within the context of supporting infrastructure in a GIS platform is still considered as a potential method for integrating the spatial and temporal differences in utility scale and household scale data inputs. More importantly, spatiotemporal modelling could also provide a means of investigating opportunities to reduce resource consumption across the utility and residential interface which leads to the final research objective and research question of this thesis:

RO 3: Propose how to integrate information from water and residential sectors to reduce WRE.

> ***RQ 3: How can information be integrated across the spatial and temporal scales needed to reduce WRE use across the residential and water sectors?***

Chapter 3. Regional Scale Variability of Cold Water Temperature: Implications for Household Water-Related Energy Demand

This chapter includes a slightly modified co-authored paper which addresses the first research objective (RO) and research question (RQ) of this thesis:

RO 1: Investigate the water utility influence on residential WRE use through the water supply temperature.

RQ 1: How does the variation in cold water temperature impact residential WRE use?

This chapter connects the water infrastructure influence on residential WRE use through the cold water temperature (CWT) variability. This was done by:

- Utilising spatial statistical analysis to demonstrate the impact of the CWT variation on residential energy use. This was dependent on the household's geographic location.
- Discussing the implications of CWT variability on specific hot water infrastructure standards and water quality management.
- Directly influencing the theoretical component of the residential WRE model developed in RO 2 and the concept review in RO 3.

Bors, J., O'Brien, K.R., Kenway, S.J., Lant, P.A., 2017. *Regional-Scale Variability of Cold Water Temperature: Implications for Household Water-Related Energy Demand*. Resources, Conservation & Recycling 124: p. 107-115.

Statement of Contribution: J. Bors (Candidate) – Conception and design (80%), analysis and interpretation (75%), drafting and production (60%); K.R. O'Brien - Conception and design (5%), analysis and interpretation (5%), drafting and production (30%); S.J. Kenway - Conception and design (10%), analysis and interpretation (15%), drafting and production (5%); P.A. Lant - Conception and design (5%), analysis and interpretation (5%), drafting and production (5%).

The conference paper associated with RO 1 is presented in Appendix B for completion but is not included in the body of this thesis.

3.1. Abstract

Residential water use accounts for at least 80% of water-related energy (WRE) demand (primarily through water heating) in the residential urban water system. Cold water temperature (CWT) is a key determinant in predicting residential WRE but variation of CWT within water networks has not been quantified and is not accounted for in water heating energy consumption guidelines. Here, I analysed the spatiotemporal variability in CWT over the course of a year (2013) using 5760 measurements from 1255 urban water system sampling locations across the Yarra Valley Water region in Melbourne, Australia. CWT varied across the study site from 12 to 28°C during summer and 9 to 15°C during winter. Spatial clusters of higher CWT regions (hot spots) and lower CWT regions (cold spots) were also observed. The CWT variability impact on annual household WRE demand was estimated to be between -17 to +19% (-640 to +680 kWh/hh.yr) change in water heating for sample households, which is dependent on the geographical location of the household within the study site. However, households located in cold spot regions will have almost twice the amount of WRE demand than average, conversely, WRE demand will be lower than average in hot spot regions.

Monthly mean CWTs diverged from the Australian Standards for hot water system (HWS) energy consumption guidelines value by -21 to +47%. The magnitude of CWT variability and associated energy required for water heating are comparable with the total energy used by water utilities to deliver water supply and sewage disposal services. Variation in water heating could be as large as -4.6 kWh/hh.d (hot spot in March) and 3.6 kWh/hh.d (cold spot in July), more than three times the total energy used to deliver water supply and sewage disposal services for this region. Accounting for CWT variability could increase accuracy of regional scale WRE demand and HWS performance.

3.2. Introduction

Water end use processes have significantly higher energy intensity than the energy required for water supply and sewage disposal services [21, 40, 103, 138]. At least 80% of WRE demand in the residential urban water supply system is caused by household water use [56, 64]. However, residential WRE is often not considered by utilities and end users. This may be because water utilities have little direct control over WRE in households. Widening the water utilities perspective on energy use to include residential WRE demand presents opportunities to attain whole-of-system reduction in WRE demand of urban water systems [39]. For example, solar hot water systems (SHWSs) can reduce WRE by 50-85% for an average household [110], thereby significantly reducing related GHG emissions. Minimising residential WRE demand is therefore important in ensuring long-term sustainability of urban water systems.

The indirect implications of water management on WRE have not been greatly considered [90], in particular, the impact of CWT on residential WRE demand through water heating energy consumption [68, 86]. For example, Kenway et al. [94] observed that a 2°C reduction in CWT could increase household WRE demand by 6%. Correspondingly, Kaufmann et al. [71] estimated a 1°C rise in CWT could reduce state-wide annual residential natural gas consumption by 5.6%. Water utility management of CWT in the distribution network has potentially, a substantial influence on household WRE demand.

There is significant evidence that CWT is not a constant value in water distribution networks but varies spatially and temporally [73, 81, 87, 139]. Thus, quantifying the spatiotemporal variability of CWT is important for estimating household WRE demand. For instance, a constant CWT of 15°C is often assumed in calculations for the daily energy consumption of electric hot water systems (EHWSs) [93] and the minimum energy performance of gas hot water systems (GHWSs) [140] whilst SHWS performance is assessed using average monthly CWT values derived by dividing Australia into four climate zones [89]. However, the assumption of constant CWT values within each climate zone can introduce errors in predicting energy changes in large scale adoption of SHWSs [141]. The spatiotemporal variability of CWT may therefore be important to regional scale predictions of WRE demand. Moreover, more accurate CWT values could enable more accurate predictions of changes in household WRE demand in response to policy, infrastructure and market changes (e.g. increased use of SHWSs through state government rebate schemes to achieve state government renewable energy targets).

Many factors could be contributing to the observed spatial and temporal variability of CWT in water distribution networks. For instance, ambient air temperature affects CWT at the source (e.g. reservoir water temperature) [142] and through the distribution network (e.g. ground temperature) [81]. Studies also reveal a rise in regional urban subsurface temperatures [143-145] which could contribute to higher CWTs. CWT also interacts with the built environment. For example, position of water pipes relative to other infrastructure and landscape features (e.g. roads, groundwater, and forested areas). Additionally, in many urban water systems, water is stored temporarily in above-ground metal tanks which could affect local CWT. The temperature of the source water may vary substantially (e.g. desalination, recycled water, reservoirs at different altitudes and depths) and thus also has the potential to affect CWT in the distribution network. In practice, the observed variability in CWT is likely to be caused by a combination of factors, which probably vary across the water distribution network and over time. Investigation of these factors is not possible. In this paper however, our work opens the possibility and need to understand them in future.

Previous studies have demonstrated the increasing importance of utilising spatiotemporal analysis techniques in determining: (i) urban water use for urban water management [146-149], and (ii) residential water heating for urban energy management [137, 150, 151]. In this study, spatial analysis of CWT data was used to identify statistically significant spatial variations of CWT across a subset of the Melbourne water distribution network. The associated CWT variability impact on residential WRE demand was evaluated using previously published results for CWT impact on household energy use presented in Kenway et al. [94]. The objective of the research was to: (i) use spatial statistical analysis to identify spatiotemporal variations in CWT, (ii) examine the relationship between CWT and the potential impact on household energy use, and (iii) examine the relationship between CWT and HWS standards. This work was conducted as part of a wider project including collaboration across research, industry and government.

3.3. Method

3.3.1. Study area

The Yarra Valley Water (YVW) utility service area was selected for the main study site (Figure 3-1 (a-c), -37.97°S to -37.39°S, 144.80°E to 146.17°E). This area covers approximately 4000 square kilometres and includes 671,000 residential properties in Melbourne, Australia [152]. The region is classified as a temperate climate with no dry season, mild to warm summers, cold winters and a median annual rainfall over 800mm [153].

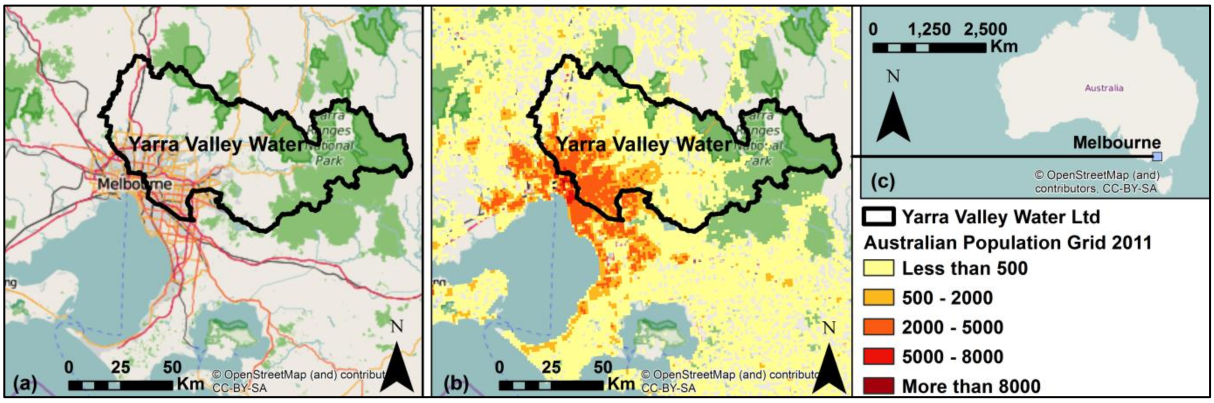

Figure 3-1: (a) Study site: Yarra Valley Water Ltd water authority service area in Melbourne [154], (b) Australian population density per 1km^2 [155], and (c) overall location.

3.3.2. Data and statistical analysis approach

YVW provided a dataset of 29,997 CWT measurements taken from 1,496 sampling locations at frequency intervals of approximately four times per year over five consecutive years (2009-2013) covering the YVW water service area. GIS files of the water infrastructure layout and the YVW business boundary were also provided to assist with assessing the underlying patterns in the distribution of CWT effects on residential WRE demand. Georeferenced CWT sampling locations were converted to shapefiles using the software ArcGIS 10.3 [156].

There were three distinct stages of analysis in this study:

(i) *Characteristics of seasonal range of CWT across 5 years*. Characterised the seasonal range of CWT data from 2009-2013.

(ii) *Spatial analysis of CWT across YVW region for 12 months.* Assessed the spatial variability of CWT for each month of 2013 (January-December) using ArcGIS 10.3.

(iii) *Monthly CWT and WRE demand*. Characterised monthly CWT from stage 2 results, the associated impact on household WRE demand using CWT sensitivity results from Kenway et al. [94] and the CWT deviation from HWS energy consumption standards.

3.3.3. Characteristics of seasonal range of CWT across 5 years

Temporal variability of the CWT entering households situated within the geographical region serviced by YVW was characterised through box and whiskers plots of pooled CWT data for each month 2009-2013. Previous investigations found that there may be a slight increase in inter-annual CWT in the study area over time, but that this increase was small compared to spatial and seasonal variability and could not be verified statistically due to changes in sampling methods [157]. Thus, time-series analysis of inter-annual spatial variability in CWT is not included in this paper.

3.3.4. Spatial analysis of CWT across YVW region for 12 months

In the second stage of analysis, it was important to investigate whether or not CWT measurements were randomly spread or if there were significant spatial patterns of measurements. The spatial variability in CWT data was quantified using the *Hot Spot Analysis* tool in ArcGIS 10.3, a spatial pattern analysis technique that can identify statistically significant spatial clusters of high values (hot spots) and low values (cold spots). The *Hot Spot Analysis* tool was applied to subsets of monthly data for 12 months of the most recently available complete year of CWT measurements (5760 measurements were taken between January-December 2013 from 1255 sampling locations). The null hypothesis for this type of spatial pattern analysis is ‘Complete Spatial Randomness’ [130], i.e. the CWT values are randomly spread across the YVW service area. The null hypothesis can be rejected when there is a statistically significant spatial cluster of CWT measurements. Statistically significant spatial clusters signify that data values are not attributed to random chance and there is an underlying spatial process at work [158].

The spatial statistic technique (mathematics) behind the *Hot Spot Analysis* tool is the Getis-Ord $G_i^*\ (d)$ local statistic [158] (Appendix C.2). The calculated $G_i^*\ (d)$ output of each CWT measurement is a z-score (measure of standard deviation) demonstrating the statistical significance of normally distributed CWT values and a corresponding p-value (probability) demonstrating the confidence level of the z-score. The $G_i^*\ (d)$ statistic can separate clusters of high values from clusters of low values [159]. A cluster of high CWT values (hot spot) was indicated by a statistically significant positive z-score whilst a cluster of low CWT values (cold spot) was indicated by a statistically significant negative z-score. Statistical significance was determined at the 90% ($p<0.1$), 95% ($p<0.05$) and 99% ($p<0.01$) confidence levels. Additionally, an adjustment to the critical p-value used for each confidence level was made through the *False Discovery Rate Correction* method which addresses issues with both the potential for false positives and the potential for artificially inflating statistical significance [160]. A summary of z-scores and critical p-values for each confidence level is presented in Appendix C.3, Table C-1.

In studies where the mechanisms driving spatial variability are known, that information can be used to inform the spatial scale of analysis required to run the *Hot Spot Analysis* tool [130]. In this study, the physical mechanisms driving CWT variability are not well known. Therefore, the scale of spatial analysis was determined from the minimum number of neighbouring sample points required for statistical significance. The sampling location density varied from very high (southwestern corner of the study) to very low (north-eastern side of the study site) in line with population density (see Figure 3-1 (b)). The *Optimised Hot Spot Analysis* tool (i.e. automated version of the *Hot Spot Analysis* tool, also available in ArcGIS 10.3) was run for each subset of monthly CWT measurements to determine the minimum neighbourhood size (i.e. scale of spatial analysis) at which the spatial differences in CWT were statistically significant in every month. The minimum neighbourhood size ranged from 5 to 7 km (see Appendix C.3, Table C-2). Therefore, the hot spot analysis was run at 7 km to ensure a large enough sample size was available to quantify spatial variability in all neighbourhoods in each study month. The minimum neighbourhood size reflects the spatial resolution and variability in sampling, as well as the spatial scale of the processes which are driving the variability in CWT.

Three types of zones (Not Significant, Hot Spot and Cold Spot) were spatially mapped for each month of data in 2013. These were created from interpolation of z-scores. The z-scores rather than CWT values were interpolated to demonstrate the statistically significant variability in CWTs across YVW (i.e. hot spots and cold spots). The z-scores were interpolated using the *Spline with Barrier* tool in ArcGIS v10.3. The spline barrier was specified as the YVW service boundary and the surface classification intervals were specified using the z-scores for each confidence level (Not significant, 90%, 95% and 99%). Spline interpolation has previously been widely used to demonstrate the spatial distribution of climate variables such as temperature [161]. The advantage of using this method is that the surface is created with the specified sample points and the values between sample points are determined using a minimum curvature spline technique [162].

3.3.5. Monthly CWT and WRE demand

Results from the second stage of analysis were used to characterise the YVW mean CWT for 12 months (January-February 2013). Sampling locations identified as either hot spots or cold spots (at 99% confidence level) were counted and the corresponding hot spot maximum CWT and cold spot minimum CWT were used to characterise the upper and lower bounds of CWT variability across the study site. Hot spot analysis characterisation (mean, min, max, counts) of sampling locations identified as hot spots or cold spots at 90%, 95% and 99% confidence levels along with the characterisation of 'Not Significant' regions are presented in Appendix C.3, Table C-1.

The YVW mean CWT, hot spot maximum CWT and cold spot minimum CWT, were compared with CWT values in Australian HWS energy consumption standards which enabled a preliminary evaluation of the study sites CWT deviation from standardised CWTs.

The CWT variability impact on household WRE demand was based on the preliminary sensitivity results of a 10% change in CWT for the seven households reported in Kenway et al. [94]. The sensitivity analysis results were derived from a mathematical material flow analysis (MMFA) model purposely built for the detailed characterization of household WRE demand. The MMFA model was previously published in Kenway et al. [68].

The potential range (upper and lower limit) of CWT influence on household WRE demand reported in Kenway et al. [94] was used as the upper and lower limits of CWT impact in this study (Table 3-1). In Kenway et al. [94], the impact of a 10% change in CWT on household WRE demand was evaluated from an annual average CWT for all HWS end uses such as showering, clothes washing and dishwashing etc. For this study, a monthly average CWT for all HWS end use is applied. Thus, the monthly estimation of the CWT variability impact on household WRE demand is calculated from the monthly CWT deviation away from the reference CWT values in Kenway et al. [94] and the corresponding impact on WRE demand (Table 3-1). Moreover, it was assumed that for each additional 10% change in CWT, the impact on household WRE demand would change by the amount specified by the previous study (Table 3-1). An important basis for this study is the assumption that environmental, technological and behavioural characteristics of the seven households reported in Kenway et al. [94] would stay the same for all households within the study site throughout 2013.

Table 3-1: Summary of CWT impact on household WRE demand from Kenway et al. [94].

Range of Impact	CWT Mean (°C)	WRE Demand, Total (kWh/hh.d)	10% Change in CWT (°C)	10% Change in CWT Impact on WRE[a] Demand (kWh/hh.d)
Upper Limit[b]	16.3	10	+1.63	-0.63[b]
Lower Limit[c]	16.9	5	+1.69	-0.29[c]

[a] Note an increase in CWT causes a decrease in WRE demand and vice versa. [b] Upper limit is defined as the highest impact on WRE demand resulting from a 10% change in CWT. [c] Lower limit is defined as the lowest impact on WRE demand resulting from a 10% change in CWT.

3.4. Results

3.4.1. Characteristics of seasonal range of CWT across 5 years

A strong seasonal signal was present in the CWT recordings with higher variability in summer (December-February) and lower variability in winter (June-August) (Figure 3-2 (a)). The range in CWT across the YVW region was largest during summer (12-28°C) and smallest during winter (9-15°C) (Figure 3-2 (b)). Variations of CWT between summer and winter were greater than variations of CWT between sampling locations. Peak monthly average CWTs occurred during February (mean: 21-23°C) whilst the lowest values occurred during July (mean: 11-12°C). The range in CWT across the YVW region (Δ16°C summer, Δ6°C winter) suggests that testing for statistical significance of CWT variability is needed whilst the strong seasonal signal suggests that monthly time steps should be used to investigate the spatial patterns in CWT variability across the study site.

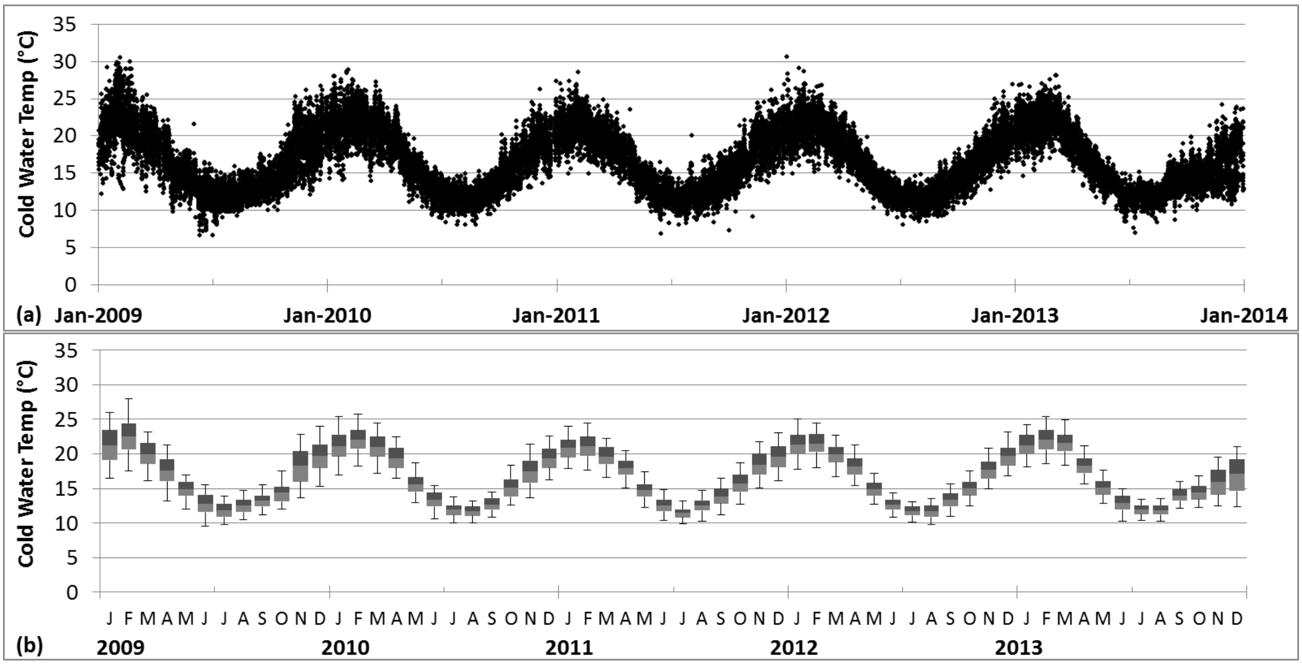

Figure 3-2: (a) Seasonal signal in the CWT across the study site; (b) Monthly statistics of CWT variation across five consecutive years (2009-2013).

3.4.2. Spatial analysis of CWT across YVW region for 12 months

Spatial patterns of statistically significant higher and lower CWT regions changed throughout the study year (Figure 3-3 (a-l)). Each hot spot analysis of monthly CWT data showed hot spots and cold spots at 90%, 95%, and 99% confidence levels.

Hot spot analysis results demonstrate that the null hypothesis of 'Complete Spatial Randomness' (i.e. CWT values were randomly spread across the study site) can be rejected. The hot spot and cold spot zones illustrated in Figure 3-3 show statistically significant spatial clusters of higher and lower CWTs, thus indicating an underlying spatial process is influencing the CWT in the water distribution network. The clusters could be affected by the distribution of the sampling locations. However, the spatial variability in CWT is not caused by the spatial variability in sampling alone. Whilst sampling is not uniform spatially, it is consistent temporally i.e. an area with high sampling density will have a high sampling density in every month. Therefore, the movement of clusters demonstrates an independent spatial process is influencing CWTs.

Hot spots were mostly found in the densely populated (500-5000 people per 1 km^2), western side of the YVW major pipe network closest to the centre of Melbourne city. As the year progressed, the hot spots gradually moved towards the southwestern tip of the YVW major pipe network that was still within a densely populated region. Hot spots were similar in size across different months except for June where only two water sampling locations were identified as hot spots at 99% confidence level.

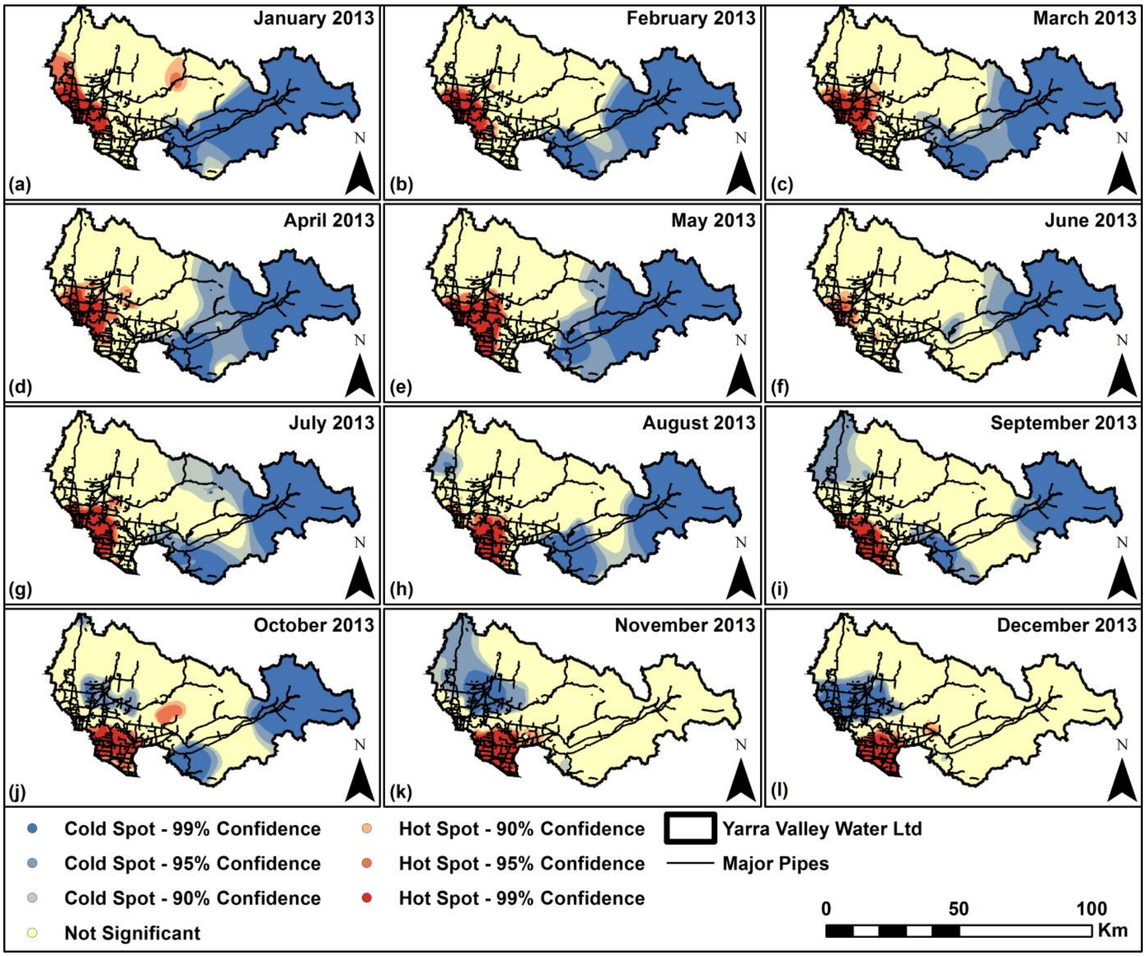

Figure 3-3: (a-l) Statistically significant clusters of higher CWTs and statistically significant clusters of lower CWTs across the Yarra Valley Water Ltd service area, 2013.

Cold spots were mostly found in the higher altitude, sparsely populated (<500 people per 1 km^2), eastern side of the YVW major pipe network covered by bushland. Cold spots were similar in size, shape and location from January to May then gradually reduced in size. A cold spot started to emerge on the densely populated western side of the study site in August and gradually grew into a highly significant cold spot (from October to December) that settled over the previously occupied urban hot spots from earlier in the year. This may indicate a change in operational conditions, for example, a change in source of water supply therefore a change in water supply temperature. Additionally, there is an absence of cold spots in the higher altitude eastern side of the study site during November and December although cold spots were observed in this area from January to October. This suggests the potential cause of CWT variability in this region either didn't exist or was deterred during the latter part of the year. For example, warmer weather conditions may have resulted in warmer source water temperature.

3.4.3. Monthly CWT and WRE demand

Monthly CWTs characterised for the YVW study site (Table 3-2) generally followed the annual water temperature cycle displayed in Figure 3-2. The hot spot maximum CWTs were higher than YVW mean CWTs by 6-41% whilst cold spot minimum CWTs were lower than YVW mean CWTs by 22-41%. Monthly CWTs diverged from the assumed value of 15°C used for daily energy consumption calculations of EHWSs and minimum energy performance calculations of GHWSs (YVW mean CWT: -21 to +47%, hot spot max CWT: -9 to +87%, cold spot min CWT: -53 to +12%). Similarly, monthly CWTs diverged from standardised CWT values used for SHWSs performance evaluation in Melbourne (YVW mean CWT: -11 to +49%, hot spot max CWT: +26 to +83%, cold spot min CWT: -41 to -1%).[1] The exception was the cold spot minimum CWT value for May which was in good agreement with the Standard. Note the annual average CWTs (i.e. average of monthly averages, YVW mean CWT: 16.4°C, hot spot max CWT: 20.9°C, cold spot min CWT: 11.5°C) yield significantly different results.

Table 3-2: Monthly temperature characterisation and corresponding number of sample points for: AS/NZS Standard CWT[a], YVW mean CWT, hot spot[d] maximum, cold spot[d] minimum.

Month	AS/NZS	YVW	Not Significant Zone		Hot Spot Zone		Cold Spot Zone	
	Standard[a] CWT (°C)	Total Samples[b]	YVW Mean CWT (°C)	Sample Size[c]	Maximum[d] CWT (°C)	Sample Size[c]	Minimum[d] CWT (°C)	Sample Size[c]
Jan	20	542	21.3	290	26.6	109	14.6	84
Feb	20	444	22.0	252	27.0	91	16.2	51
Mar	18	460	21.6	241	28.1	95	16.8	39
Apr	15	486	18.3	212	22.6	91	13.3	47
May	11	501	15.2	213	18.9	150	11.0	54
Jun	9	435	12.9	327	13.7	2	8.9	20
Jul	8	522	11.9	276	14.6	116	7.0	40
Aug	10	511	11.9	270	14.8	90	8.8	42
Sep	12	478	14.0	249	19.0	88	8.7	33
Oct	15	508	14.4	231	19.1	82	10.0	46
Nov	17	417	16.0	205	22.0	73	11.5	44
Dec	19	456	17.1	191	23.9	90	11.2	107

[a] AS/NZS 4234:2008, Heated Water Systems – Calculation of Energy Consumption, Table A6, Zone 4 CWT values used to calculate energy consumption from water heaters in Melbourne [89]. [b] Total samples taken for monthly CWT measurements from YVWs' water quality dataset. [c] Number of samples that were identified as either "Not Significant", or a Hot Spot ($p<0.01$), or a Cold Spot ($p<0.01$) from the total samples taken. [d] Hot spot maximum CWT and cold spot minimum CWT values at 99% confidence level.

Between 16-30% of the sampling locations in each month were identified as hot spots (except June) and 5-23% of the sampling locations in each month were identified as cold spots. The hot spot

[1] Study results were compared with standardised CWT values for Melbourne SHWS performance presented in AS/NZS 4234, Table A6, Zone 4 column.

region in each month is smaller in size compared to the cold spot region but contains a larger number of sampling locations identified as hot spots due to the sampling density (see Figure 3-3 (a-l) and Table 3-2). It's important to note that hot spots are generally located in more densely populated regions than cold spots (see Figure 3-1 (b) and Figure 3-3 (a-l)). The exception to this observation is the cold spot that appears on the western side of the site during October-December.

Estimated reductions in household WRE demand occur during warmer months of the year. Presented in Table 3-3, is the estimated change in household WRE directly due to the dynamic nature of CWT. This is taking into consideration the geospatial location of the household i.e. if the household was connected to the water infrastructure in a neutral zone, hot zone or a cold zone. CWT variability impact on household WRE demand was estimated using the YVW mean CWT, hot spot maximum CWT and cold spot minimum CWT. The largest estimated reduction in household WRE demand occurred during March (38-46%). The large reduction in WRE demand is due to higher CWTs in hot spot regions which require less energy to reach the HWS outlet temperature of HWSs (hot spot max CWT, 28.1°C). Similarly, the largest estimated reduction in WRE demand for households across 'Not significant' regions occurred during February (18-22%, YVW mean CWT: 22.0°C). Only a minor reduction in WRE demand is estimated for households in cold spot regions (2%, cold spot min CWT: 16.8°C).

Table 3-3: Estimated change in monthly household (hh) WRE demand due to CWT variability.

Month	Not Significant Zone Change in WRE demand				Hot Spot Zone[c] Change in WRE demand				Cold Spot Zone[c] Change in WRE demand			
	ΔkWh/hh.m[a]		Δ%[b]		ΔkWh/hh.m[a]		Δ%[b]		ΔkWh/hh.m[a]		Δ%[b]	
	L	**U**	**L**	**U**	**L**	**U**	**L**	**U**	**L**	**U**	**L**	**U**
Jan	-23	-60	-15	-19	-52	-123	-33	-40	+12	+20	+8	+7
Feb	-25	-62	-18	-22	-49	-116	-34	-41	+3	+1	+2	0
Mar	-24	-62	-16	-20	-60	-141	-38	-46	+1	-6	0	-2
Apr	-8	-25	-5	-8	-29	-73	-20	-24	+19	+34	+12	+11
May	+9	+14	+6	+5	-11	-31	-7	-10	+31	+64	+20	+20
Jun	+21	+39	+14	+13	+16	+30	+11	+10	+41	+86	+27	+29
Jul	+27	+53	+17	+17	+12	+20	+8	+7	+53	+111	+34	+36
Aug	+27	+53	+17	+17	+11	+18	+7	+6	+43	+90	+28	+29
Sep	+15	+26	+10	+9	-11	-31	-7	-10	+42	+88	+28	+29
Oct	+13	+22	+8	+7	-12	-34	-8	-11	+37	+75	+24	+24
Nov	+5	+4	+3	+1	-26	-66	-17	-22	+28	+56	+19	+19
Dec	0	-8	0	-3	-37	-91	-24	-29	+30	+61	+20	+20

[a] ΔkWh/hh.m is the estimated change in kWh of WRE per household per month due to CWT variability. [b] Δ% is the estimated change in the % of WRE per household per month due to CWT variability. [c] Hot spot maximum CWT and cold spot minimum CWT impact on WRE demand at 99% confidence level. L (lower) and U (upper) limit scenarios of estimated CWT impact on WRE demand (see Table 3-1).

Estimated increases in household WRE demand occur during winter months. The largest estimated increase in household WRE demand occurred during July (34-36%). The significant increase in WRE demand is due to lower CWTs in cold spot regions which lead to an increase in the HWS energy consumption of HWSs (cold spot min CWT 7.0°C). Similarly, the largest estimated increase in WRE demand for households across 'Not significant' regions occurred during July and August (17%, YVW mean CWT: 11.9°C). CWTs for YVW, hot spots and cold spots have been predicted to increase household WRE demand during winter. The largest potential increase in WRE demand due to higher CWTs in hot spot regions is estimated to be 6-11%.

3.5. Discussion

3.5.1. Impact on household WRE

An unexpected outcome of this study is that many households in the YVW service area are likely to benefit from higher CWTs in hot spots. In hot spots, higher CWTs means households in these areas will require less WRE demand than the average household. The hot spots in this study are located across the densely populated western and southwestern side of the study site. The maximum potential reduction in household WRE in hot spot regions occurs during January-March and December (33-40%, 35-41%, 38-46%, and 24-29% per household), corresponding to a potential reduction in total energy use by 4-11% (-37 to -141 kWh/hh.m) for households studied in Kenway et al. [94]. This indicates that households in hot spot regions achieve lower WRE demands than average, at a time of year when residential space cooling demands of households are at their peak. Additionally, the higher CWTs in hot spots during winter will lead to lower WRE demands than average when residential space heating demands are at their highest.

The cold spot zones have the potential for greatest WRE demand per household. Households located in cold spot regions will have almost twice the amount of WRE demand (due to lower CWTs) than the average household. However, the number of households that have increased WRE demand due to cold spots is far fewer than the number of households that have reduced WRE demand due to hot spots (see Figure 3-1 (b) and Figure 3-3 (k-l)). This may not be the case during November-December where the cold spot region is situated across a densely populated area (see Figure 3-1 (b) and Figure 3-3 (k-l)). The WRE difference between cold spot regions and the rest of the YVW will be greatest during November (19% per household) and December (20% per household) in 2013. Spatiotemporal analysis of CWT variability highlights the regions that will have the most impact on household WRE demand.

A key point of comparison for this study is the energy used by water utilities to provide water supply and sewage disposal services against the CWT impact on household WRE demand. Saliba and Gan [134] developed an energy density map for the study site that estimated the water utility primarily used between 0.5-1.5 kWh/hh.d when providing water supply and sewage disposal services to an average water use household (500 L/hh.d). Comparatively, the potential CWT impact on household WRE is between -4.6 kWh/hh.d (hot spot in March) to 3.6 kWh/hh.d (cold spot in July) for the study area.[2] Therefore, the estimated CWT impact on household WRE can be up to three times the amount of energy required for combined water supply and sewage disposal services depending on the geographic location of the household with respect to the water infrastructure asset. Thus, mitigating CWT variability presents an opportunity for water utilities to reduce residential WRE demand.

From a broader perspective, the CWT impact on household energy consumption is comparable with the urban heat island (UHI) impact on building energy consumption. UHI studies have surmised that the UHI effect essentially increases building energy consumption during summer [163-165] but also decreases building energy consumption during winter [166-168]. Hirano and Fujita [167] reported that annual energy consumption for water heating decreased by 6.8% due to UHI effects.[3] In comparison, the CWT variability in YVW is estimated to affect annual WRE consumption by -17% to +19% for individual households. In other words, the CWT impact on annual household WRE demand could be between a 17% reduction (-640 kWh/hh.yr) in water heating and a 19% increase (+680 kWh/hh.yr) in water heating, depending on the geographical location of the household within the study site. While these studies were in different locations, the estimated energy impact of CWT variation on household WRE demand was comparable in magnitude to the UHI effect on household water heating.

3.5.2. Implications for regional water and WRE management

Variation in CWT has three implications for managing regional scale water and WRE: (i) HWS performance evaluation for more accurate energy labelling, (ii) regional scale prediction of

[2] CWT impact on household WRE calculations are based on CWT deviations away from the CWT base case temperature of 16.9°C for HH3 as described in Kenway et al. (2014), a study on the detailed WRE characterization of 7 households.

[3] Hirano and Fujita (2012) reported results for the residential sector and commercial sector combined although the reduction in water heating was predominantly for the residential sector.

displaced energy savings for issuing renewable energy certificates, and (iii) highlights the issue of WRE jurisdiction.

Accounting for CWT variability may require changes in energy labelling of HWSs. For example, in typical EHWS specifications (AS1056.4, Table C1), an assumed CWT value of 15°C is applied [93]. The standard provides a method for checking whether the energy consumption capacity of a specified EHWS would be able to meet one of three hot water use draw-off profiles (flat, morning, evening peak) for two possible energy supply scenarios (restricted off-peak or extended off-peak). Under static modelling conditions, CWTs are considered to have a negligible impact on off-peak energy use [93]. However, without accounting for CWT variability, current EHWSs operating on off-peak energisation schemes may not deliver the expected performance conditions of the assigned EHWS energy label e.g. providing the required volume of hot water at the required time.

Variability in CWT may also affect renewable energy certificate allocations. Renewable energy certificates are tradable instruments that represent the use of a suitable source of renewable power to replace the use of coal-based electricity [169]. For the Australian case, the standard annual energy use of SHWSs is required for evaluating potential energy savings and allocating renewable energy certificates [141]. A minimum delivery temperature of 45°C needs to be satisfied when calculating the standard annual energy use of SHWSs [89]. Higher starting CWTs are estimated to yield a smaller standardised annual energy use and vice versa. Standardised CWT values for SHWSs in Melbourne (AS/NZS 4234, Table A6, Zone 4) under-predict or over-predict the YVW mean CWTs (Table 3-2), therefore it is difficult to estimate the overall impact of CWT variability on standard annual energy use for SHWSs. Thus, it is difficult to estimate the total amount of electricity that is likely to be displaced by SHWSs without running YVW mean CWTs through the Transient System (TRNSYS) simulation software specified in the AS/NZS 4234 standard. The apparent lack of agreement between the YVW mean CWTs and standardised CWTs indicates that CWT mapping may be beneficial when determining the potential energy savings of SHWSs required for issuing renewable energy certificates.

The CWT variability impact on household WRE demand highlights the issue of WRE jurisdiction. There has been a focus of efforts to reduce the WRE footprint of water utilities [39] which is at best, 20% of the residential urban WRE [64] with the remaining 80% attributed to households. In some areas, CWT variability is estimated to impact households three times more than the energy used by water utilities to provide urban water services. However, CWT management is not a primary water management practice [170]. Consequently, the impact of CWT variability in the water distribution network is currently borne by the resident and not the utility even though substantial reductions in regional scale residential WRE demand could potentially be achieved through utility management of CWTs in cold spot zones. For example, the cold spot in December is estimated to impact 25,000 households at a maximum increase of 61 kWh/hh.m (see Figure 3-3 (l), Figure 3-1 (b) and Table 3-3, respectively), potentially affecting up to 1525 MWh/m of residential WRE demand in a small subsection of Melbourne's water distribution network during December. Comparatively, this is 0.1% of the Victoria state governments 2020 renewable energy target [171]. State government renewable energy targets could be an important incentive for water utilities to include CWT management for reducing regional scale residential WRE demand.

3.5.3. Broader implications for urban water management

While elevated CWT in some regions may reduce energy required for water heating and thus WRE demands, warmer water supply can increase risks to human health. Australian drinking water CWTs range between 10-30°C whilst European Economic Community guidelines recommend a maximum CWT value of 25°C and Canadian guidelines recommend a CWT of 15°C [170]. A general goal of water quality guidelines is to attain biological stability in drinking water systems however, recent findings show this may be difficult to achieve in complex water distribution systems [172]. One concern is *Naegleria fowleri* which grows between 18-46°C and has previously been an issue in a number of Australian drinking water systems [170]. Another concern is *Legionella* which is able to colonise hot water and cold water drinking systems [173, 174]. Specifically, CWTs of 20-37°C increase the reproduction rate of *Legionella* bacteria [175]. Both *Naegleria fowleri* and *Legionella* thrive in environments that overlap with the CWTs presented here. Water quality assessment and analysis on microbial communities was not included in the scope of this study nevertheless hot spot results highlight regions that are potentially at risk for waterborne disease. Thus, maps of CWT variability are useful not just in evaluating energy demands, but also in assessing water quality risks.

3.5.4. Research limitations and directions for future work

The hot spots and cold spots were determined using neighbourhood size of 7 km. This scale of spatial analysis was selected based on statistical analysis of the data, rather than a mechanistic understanding of the factors driving the variability. At lower resolution, variability was typically not significant, but at larger scales, spatial variability was evident. Therefore, the underlying processes driving the variability is not known, the statistics suggests that the variability is driven at scales of order 7 km. While the specific hot spots and cold spots defined here depend on the scale of spatial analysis, our analysis demonstrates clearly that there is significant spatial and temporal variability in CWT across the YVW region, and that this variability is large enough to affect WRE demand.

The temporal scale of analysis was selected on the monthly patterns of raw CWT measurements. As demonstrated in Figure 3-3, there were months where there was a repeating pattern of hotspot and cold spot locations thus, a seasonal pattern emerged in the spatial movement of CWT variability. Therefore, it is recommended that temporal scale boundaries be clustered seasonally in future spatiotemporal modelling of CWT variability.

The basis of the CWT variability impact on household WRE analysis is the assumption that environmental, technological and behavioural characteristics of water and energy use for the seven households reported in Kenway et al. (2014) stay the same for all households within the YVW distribution region throughout 2013. Even though characteristics of household WRE demand vary significantly from one household to the next, the simplification in this study enabled the estimation of the spatiotemporal variability of CWT impact on household WRE demand. Consequently, a key outcome of this study is the importance of refined spatial scale modelling of CWTs (at least district scale) and refined temporal scale modelling of CWTs (at least monthly scale) in predictive models of household WRE demand.

The key issues that remain unresolved are: (i) the cause/s of CWT variability within the asset network, and (ii) implications for water infrastructure standards. Addressing these issues is a major step towards costing infrastructure decisions that either stabilize CWTs for CWT management in large scale water infrastructure (e.g. water asset) or account for CWT variability in small scale water infrastructure (e.g. HWSs). Potential areas for reviewing large scale water infrastructure standards to stabilize CWT for CWT management include: (i) the depth at which the water infrastructure is laid, and (ii) the insulation levels of above-ground interim water storage tanks or pipelines. Potential areas for reviewing small scale water infrastructure standards to account for CWT variability include: (i) HWS performance evaluation, and (ii) displaced energy savings calculations for issuing renewable energy certificates. Nevertheless, until these issues are resolved, the next step is to include CWT variability in regional predictions of residential WRE demand to target key areas for reducing energy consumption.

3.6. Conclusion

Statistical analysis was used to identify spatiotemporal variation of the distributed water temperature and its potential impact on household WRE demand in a subset of Melbourne's urban water distribution network (2013). The spatiotemporal variability of CWT was:

- Highest during summer (Δ16˚C) and lowest during winter (Δ6˚C). Spatial clusters of higher CWT regions (hot spots) and lower CWT regions (cold spots) were observed.
- Estimated to impact household WRE demand by -17 to +19% (-640 to +680 kWh/hh.yr) change in water heating for sample households. However, households in cold spot regions have almost twice the amount of WRE demand than average, whilst households in hot spot regions will have less WRE demand than average.
- Estimated to be as large as -4.6 kWh/hh.d (hot spot in March) and 3.6 kWh/hh.d (cold spot in July), more than three times the total energy used to deliver water supply and sewage disposal services for this region.
- Evaluated to diverge from the Australian Standard HWS energy consumption guidelines by -21 to +47%. This implies a significant prediction error for estimates of residential WRE demand and associated GHG emissions savings when assessing HWS performance and issuing renewable energy certificates.

In light of this work, the following recommendations have emerged as a means of reducing WRE use across residential urban water systems. Policy level recommendation is the investigation into updating CWT values for Australian Standards HWS energy consumption guidelines. It is also recommended that maps of CWT zones be produced and made available for public knowledge. Water utility level recommendations include an investigation into best practices for upgrading water infrastructure to reduce CWT variability impact on household WRE use. This could be proposed as a potential carbon offset scheme for water utilities. Household level recommendation is an additional infrastructure upgrade, moreover, additional insulation for hot water system pipes exposed to ambient air temperature. The individual level recommendation is the adjustment of hot water usage behaviour in line with CWT zone maps.

This work identifies the potential for utilities to attain a whole-of-system reduction in the WRE demand of residential urban water systems through CWT management. There is new evidence on how water and energy are interconnected and consequently, why they need joint consideration across the water and residential sectors within the residential urban water cycle.

Chapter 4. Demographics, Technology, Behaviour and Environmental Variability Affect Regional Consumption of Water and Water-Related Energy

This chapter addresses the second research objective (RO) and research question (RQ) of this thesis:

RO 2: Develop a method to quantify the residential influence on regional WRE use.

> ***RQ 2: How does household scale technology and behaviour affect regional water, WRE use and associated emissions?***

This chapter connects the residential influence on regional water, WRE use and associated emissions. This was done by:

- Developing a regional scale residential WRE model by scaling up the household scale residential WRE model described in Kenway et al. [68] utilising census data and local water authority information to characterise end use variability between individual households.
- Conducting a scenario analysis of water utility decisions through technological changes in households and scenario analysis of household decisions through behavioural changes associated with each technological change.
- Discussing the factors affecting household consumption, impact of scenarios on regional consumption, and the implications of regional water and WRE management, specifically the WRE implications of rebate schemes targeting water efficiency.
- Directly influencing the theoretical component of the concept review in RO 3.

4.1. Abstract

The four biggest determinants of water and water-related energy (WRE) consumption are household composition, hot water system (HWS) type, shower use, and clothes washer use. This study investigates how interactions between these factors affect water and WRE consumption. A household scale material flow analysis model, ResWE, is used here to construct a regional scale model of water, water-related electricity and gas consumption, and associated greenhouse gas (GHG) emissions, using local water authority information to characterise end use variability between individual households. The model was run on a monthly timestep across the study site in Melbourne, Australia, for scenarios of technological, behavioural and demographic change.

Shower systems were found to be the largest lever for reducing resource consumption, with estimated potential for annual water reduction of 27% (0.8 GL/yr), WRE-electricity reduction of 15% (2.3 GWh/yr), WRE-gas reduction of 48% (23.9 GWh/yr), and WRE-GHG reduction of 28% (7.8 kt$CO_{2\text{-}e}$/yr), based on changes in both technology and behaviour. Clothes washing use highlights the importance of interactions between technology and behaviour for reducing regional resources: increasing the penetration of top loaders to 100% increased regional water use by 5% and had minimal impact on regional WRE because top loaders used less energy than front loaders for a cold wash cycle. Household composition was a significant factor in more efficient resource consumption. Small households were the highest consumers per capita: 53% of the population lived in 73% of the household stock and consumed 59% of resources. In contrast, large households were the lowest consumers per capita. These results demonstrate how interactions between technology and behaviour ultimately determines water and WRE consumption, thus, such interactions need to be taken into consideration in formulation of policy aiming to reduce water and energy consumption at the regional scale.

4.2. Introduction

The water-energy nexus denotes the conflicting interdependence of water and energy systems where water systems use energy, energy systems use water, and an increase in one resource often results in an increase in the other. The growing need to document water-energy interactions and efficiently co-manage water and energy is widely recognised [13, 14, 18, 24]. Modelling and analysis of water-energy interactions are important to inform understanding and decision making in the management of water and energy resources [18, 37, 49].

The water-energy nexus is influenced by a complex system of dynamically changing parts that include: competing demands for water and energy, demographics, technology options, land use, policies, economics, and climate [14]. Integrated modelling spanning these domains can improve the understanding of water-energy interactions and lead to emergent insights into developing resilient water-energy systems [14].

There are numerous studies that quantify residential water and WRE associated with specific technologies and end use behaviour [79, 98] but few which quantify the cumulative impact of different technologies and changes in end use behaviour at larger scales. This is important because in dynamic systems non-linear responses can lead to unexpected outcomes. Impacts of residential WRE are driven by: infrastructure design (e.g. pipe size) [60, 70], environmental influences (e.g. ambient air temperature) [71-73, 80], water appliance technology (e.g. shower head efficiency) [48, 49, 74-76], end use behaviour (e.g. shower duration) [69, 72, 77, 78], and policies (e.g. rebate schemes) [26, 45, 64, 79]. More importantly, a residential WRE model which can simultaneously assess the impact of: mechanistic technology changes, end use behaviour changes, demographic changes, and environmental changes on large scale urban WRE use and future WRE demand is needed.

Consequently, this chapter proposes a regional scale WRE model to assess the overall impacts of large scale changes (e.g. regional changes) to WRE. It undertakes this work by adapting the household scale analysis conducted by Kenway et al. [68] to quantify residential WRE use and future WRE demand. The intended outcome of this chapter is to: (i) develop and verify a regional scale WRE model that captures household heterogeneity for a specific region, (ii) quantify the impact of household decisions on residential WRE use at household and regional levels, and (iii) quantify the impact of water utility decisions on residential water, WRE use and associated GHG emissions.

4.3. Method

4.3.1. Overview

In this study, regional water use, WRE use and WRE-GHGs was modelled through scaling up a household model, ResWE, to regional scale using census data and local water authority information to characterise end use variability between individual households. The model was used to evaluate and compare changes in regional water and energy demand through technological and behaviour change scenarios, under current conditions and future demographics. Thus, the model was run across the study site for 2013 on a monthly timestep, and then run over the time frame for a number of scenarios of technological, behavioural and demographic change. ResWE, a mathematical material flow analysis model has previously been developed for quantifying household scale WRE use through ten major end use subsystems which include: (i) shower, (ii) bath, (iii) clothes washing, (iv) taps indoor, (v) dishwasher, (vi) outdoor use, (vii) toilet, (viii) kettle, (ix) air-conditioning, and (x) other energy use, as outlined in Kenway et al [68]. To date, the model has been used for assessing the WRE use of a single-family dwelling [68], a geographically dispersed group of households [69, 79], and shower use sensitivity [98]. This paper focused on the ResWE model adaptation from household scale to regional scale analysis.

4.3.2. Study area

The study site was the suburb of "Reservoir" in (Postcode 3073, Figure 4-1). Reservoir contained in 2011 a population of 47,637 people and 20,406 private dwellings [176]. Reservoir falls into the 3rd decile of the 2011 Index of Relative Advantage and Disadvantage, 2nd decile of the Index of Economic Resources, and 5th decile of the Index of Education and Occupation [177]. The site was selected within the Yarra Valley Water (YVW) region, based on: (i) availability of electricity and gas use data for model verification, (ii) a high proportion of residential land use, and (iii) nested Australian Bureau of Statistics digital boundaries to enable data aggregation for multi-scale analysis.

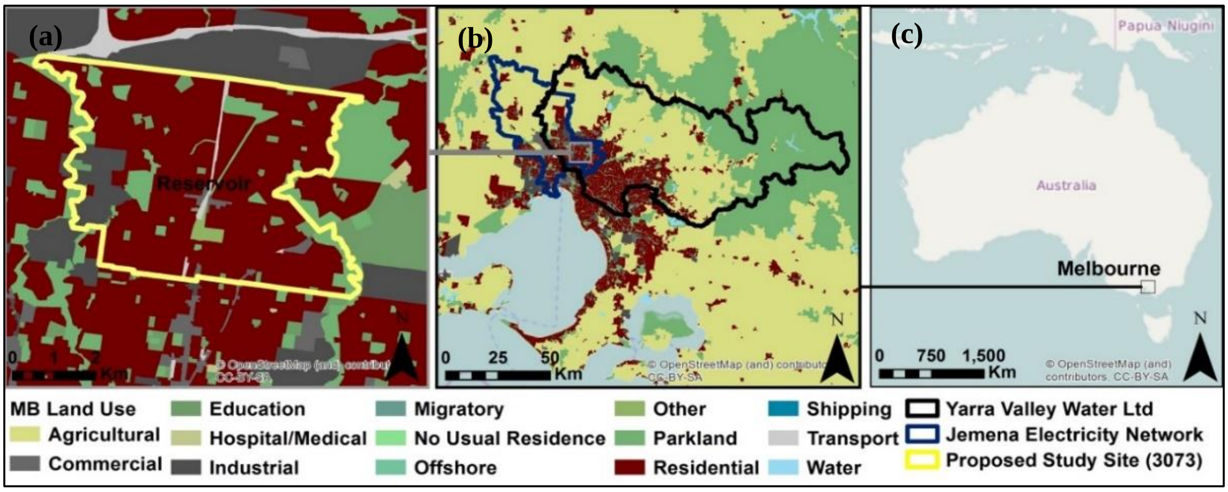

Figure 4-1: (a) Study site: Reservoir's land use classifications, Melbourne, Australia [30]; (b) Study site location within the overlap of water and electric utility project collaborators; (c) Overall location.

4.3.3. Data collection

A breakdown of household types and values for significantly influential WRE use parameters were sourced from Australian Bureau of Statistics (e.g. household composition [178], HWS type [179, 180], behavioural shower use [181], and technological clothes washer use [179]), and YVW reports (e.g. technological shower use [182] and behavioural clothes washer use [183]) (Table 4-1). In the absence of any information on key interactions between technology and behaviour of household types, it was assumed that technology and behaviour were independent.

Appliance stock specifications were sourced from Department of the Environment and Energy (e.g. electric HWSs [184], gas HWSs [185] and clothes washers [186]), Australian Standards (e.g. HWS set point [187]), and product specifications (e.g. electric and gas boosted solar hot water system (SHWS) [188] and gas continuous HWSs [189]).

Table 4-1: Summary of key data used to run and verify the regional ResWE model.

Function	Data	Spatial scale	Temporal scale	Year	Reference
Regional ResWE input data	Household composition	Postcode: 3073	Census night	2011	[178], Table B25
	HWS type	Labour force region: North Eastern Melbourne	--	2011	[179], Table 3a; [190], Table 5.2.1.1; [180], Table 3.12
	Shower use (technology)	Water utility: YVW	Season	2012	[182], Table 14
	Shower use (behaviour)	State: Victoria	Last 12 months	2013	[181], Table 18
	Clothes washer (technology)	Labour force region: North Eastern Melbourne	--	2011	[179], Table 13a
	Clothes washer (behaviour)	Water utility: YVW	Season	2011	[183], Table 17
	CWT	Postcode: 3073	Month	2013	[191]
	Ambient air temperature	Weather station: Essendon airport	3 hours	2013	[192]
	Non-significant ResWE model input parameters	Average of 5 households: YVW	Day	2012	[69]
Verification data	Water use (empirical)	Household: Reservoir	Quarter	2013	[193]
	Wastewater flow (utility model)	Sub-catchment to household: Reservoir	Week	2011, 2015	[194]
	Gas use (empirical)	Postcode: 3073	2 Month	2013	[195]
	Electricity use (empirical)	Postcode: 3073	30 minutes	2013	[196]

Data on environmental parameters and weather-related influences were sourced from the Bureau of Meteorology (e.g. ambient air temperature [192]), YVW (e.g. CWT [191]), Commonwealth Scientific and Industrial Research Organisation (e.g. indoor air temperature [197]), and Sustainable Energy Authority Victoria (e.g. SHWS fractions [198]).

Regional ResWE model parameters P1-P145 that weren't identified as significant factors were drawn from supplementary material in the household scale model study by Binks et al. [69]. Binks et al. [69] collected household scale data on a geographically dispersed group of households (n=5) in the YVW region. An average from the 5 households was used for each non-significant parameter required to run the regional ResWE model.

Model calibration data came from end use level water usage surveys carried out by water distributors within Melbourne [114-116, 199] and residential space cooling and heating data from Australian Bureau of Statistics [200, 201]. Measured water use, wastewater flow, electricity and gas use data were provided by project stakeholders (Table 4-1). Household scale water use and average household wastewater flow (utility model) were provided by the water utility, YVW [193, 194], postcode scale electricity use by electricity distributor, Jemena [196], and postcode scale gas use by the gas infrastructure manager, APA group [195].

Emissions factors for electricity and town gas were sourced from National Greenhouse Accounts [202].

4.3.4. Household ResWE model

Variability between individual households across the study site was captured through modelling the upper and lower limits of the most significantly influential WRE use factors using localised data. This was done to capture a set of conditions which led to high or low WRE use so opportunities for reducing WRE use could be identified. Previous studies have found that residential water, WRE use and associated GHGs are largely driven by the following factors: (i) household composition [50, 68, 95-98], (ii) HWS type [8, 60, 75, 80, 99-101], (iii) shower use [46, 80, 91, 98, 102-104], (iv) clothes washing use [46, 48, 103, 106-108] and (v) environmental influences [70, 71, 73, 80, 94, 98, 139]. The first four of these factors were used to characterize different households across the region (Table 4-2 to Table 4-6) and variability in environmental influences such as CWT was accounted for through running the model on a monthly time-step, with different CWTs used for each month (Table 4-7).

Considered, was 4 household compositions and 5 HWS types, which provided 20 combinations of household composition and HWS type. Each combination was used to model: (i) 2 shower head efficiency variations (ii) 2 shower duration variations, (iii) 2 clothes washer type variations, and (iv) 2 wash cycle variations (Appendix D.2, Table D-1 for the 16-shower use and clothes washing use combinations). A total of 320 household types were used to capture household end use variability (Appendix D.2, Table D-2). It’s important to note, that in the absence of any information on interactions between technology, behaviour and demographic groups, it was assumed that key factors driving residential WRE use were independent.

The ResWE model required 145 input parameters for each of the 320 household types to calculate household water use, WRE-electricity use and WRE-gas use (Appendix D.2, Table D-3). The model was run at a monthly time step to incorporate variability in environmental parameters (e.g. CWT, indoor air temperature, ambient air temperature, and SHWS fractions), and weather-related end-uses (e.g. irrigation, space heating and air conditioning).

Table 4-2: Summary of parameters used to quantify WRE use variability across a region.

Factor	Type
Household Composition (HC)	1. Family with children household; 2. Family without children household; 3. Single household; 4. Group household.
Hot Water System (HWS)	1. Electric (storage); 2. Gas (storage); 3. Gas (continuous); 4. Solar (electric boost); 5. Solar (gas boost).
Shower Use (SU)	1. Efficient shower head – low shower duration; 2. Efficient shower head – high shower duration; 3. Inefficient shower head – low shower duration; 4. Inefficient shower head – high shower duration.
Clothes Washing (CW)	1. Top loader – warm wash cycle (dual connection); 2. Top loader – cold wash cycle; 3. Front loader – warm wash cycle (single connection); 4. Front loader – cold wash cycle.

The water consumption was calculated for each month of 2013, for the 320 different household types listed in Appendix D.2, Table D-2, by aggregating ResWE predictions across the region for each specific combination of household composition, HWS type, shower use, and clothes washer use parameterizations. CWT, indoor and ambient air temperatures were specified in model parametrization for each month, along with weather-related end-use activities (outdoor water use, space heating and cooling, solar fractions). For each month, the model was run for a single day, and summed to determine monthly water and WRE use, and wastewater flows.

4.3.5. Regional ResWE model

The monthly water consumption across the YVW region depends on the water consumption of each of the 320 types (corresponding to variations in household composition, HWS type, shower use and clothes washing), and the number of households of each type (Appendix D.2, Table D-5). Then it was assumed that each of these four factors was independent, e.g. that shower use per individual was not affected by number of people in the household, HWS or clothes washer type. Therefore, the number of households of each type across the region was simply the product of N_{total}, the total number of households in the YVW region, and the proportion of households with the specific characteristics (Equation 2). Thus,

Equation 1: $N_{HC=i,HWS=j,SU=k,CW=l} = x_{HC=i}x_{HWS=j}x_{SU=k}x_{CW=l}\, N_{total}$

where $N_{HC=i,HWS=j,SU=k,CW=l}$ is the number of households in the region with household composition $HC=i$, hot water system type $HWS=j$, shower use variation $SU=k$ and clothes washing use variation CW=*l*, based on the proportion of households with composition *i* ($x_{HC=i}$), hot water system *j* ($x_{HWS=j}$), shower use *k* ($x_{SU=k}$), and clothes washer use *l* ($x_{CW=l}$).

Monthly regional water use (*Wmth_region*, (ML/month)) was determined from the number of households in each household type ($N_{HC=i,HWS=j,SU=k,CW=l}$) multiplied by the monthly water use per household in that type ($wmth_{HC=i,HWS=j,SU=k,CW=l}$, (ML/month)) calculated from the ResWE model, and summed across the 320 different household types considered in this study (Equation 2). Thus,

Equation 2: $\boldsymbol{W = \sum_{HC=1}^{4} \sum_{HWS=1}^{5} \sum_{SU=1}^{4} \sum_{CW=1}^{4} N_{HC,HWS,SU,CW}\, wmth_{HC,HWS,SU,CW}}$

The same method was used to calculate regional WRE-electricity and WRE-gas use for Reservoir from ResWE model predictions for each of the 320 household types. Emissions factors for electricity and gas were used to convert regional WRE-electricity and WRE-gas to regional WRE-GHGs.

4.3.6. Baseline model

Baseline model inputs of significant factors to scale-up the ResWE model from household to regional scale include: (i) household composition (Table 4-3), (ii) HWS type (Table 4-4), (iii) shower use (

Table 4-5), (iv) clothes washing use (Table 4-6), and (v) seasonal parameters (Table 4-7). Less significant parameters required to run the regional ResWE model were provided in Appendix D.2, Table D-3. References for parameter values presented in Table 4-3 to Table 4-7 were provided in Appendix D.2, Table D-3 whilst references for percentages of households were provided in in Appendix D.2, Table D-4.

Table 4-3: Household composition.

Household composition parameter	ResWE P#	Family with children[a]	Family without children[b]	Single	Group
No. of adults	P1	1.87	2.25	0.90	6.59
No. of children	P2	1.63	-	-	-
%. of households	-	23%	44%	29%	5%
Total no. of households	-	20,070[c]			

[a] Family with children includes dependents <15 years of age. [b] Family without children includes dependents ≥15 years of age. [c] Total number of households based on measured water use and gas use data.

Table 4-4: HWS characteristics.

HWS parameter	ResWE P#	Units	Electric storage	Gas storage	Gas continuous	Solar electric-boosted	Solar gas-boosted
Capacity	-	-	Medium	Medium	Medium	Medium	Medium
Size	-	L	160	135	-	250	250
Surface area	P16	m^2	2.47	2.12		2.58	2.58
Cold water temp.	P3	°C	See Table 4-7				
Hot water temp.	P4	°C	60	60	60	60	60
Solar fraction	P21	-	-	-	-	See Table 4-7	
Efficiency factor	P136-P145	-	1.0204	1.3106	1.5385	1.0204	1.5385
% of households	-	-	10%	56%	30%	2%	2%

Table 4-5: Shower use, technological and behavioural characteristics.

Shower use parameter	ResWE P#	Units	Value	% of households
Efficient shower head	P25, P29	L/min	6.3	21%
Inefficient shower head	P25, P29	L/min	12	79%
Short shower duration[a]	P24, P28	min	4 (summer), 4 (winter)	52.5%
Long shower duration[a]	P24, P28	min	10.3 (summer), 12 (winter)	47.5%

[a] The same shower duration was applied to both adults and children.

Table 4-6: Clothes washing, technological and behavioural characteristics.

Clothes washing parameter	ResWE P#	Units	Top loader clothes washers		Front loader clothes washer	
% of households	-	-	69%		31%	
Wash cycle	-	-	Cold wash	Warm wash	Cold wash	Warm wash
% of households	-	-	68.5%	31.5%	68.5%	31.5%
Wash cycle temperature	P60-P65	°C	See Table 4-7	40	30	40
Wash cycle energy	P54-P59	kWh	0.1962	0.1962	0.1538	0.9062
Cycle duration	P66, P67	min	75.40		220.86	
Cycle volume	P48-P53	L	117 (summer), 130 (winter)		51 (summer), 54 (winter)	
Dual connection	P70	-	Yes		No	
Standby energy	P68, P69	W	3.1		3.5	
Wash cycle frequency	P42-P47	wk^{-1}	$2.225 * (\text{Household occupants})^{0.691}$			

Table 4-7: Environmental influences and weather-related end use characteristics.

Seasonal parameter	P#	Units	Month											
			J	F	M	A	M	J	J	A	S	O	N	D
CWT	P3	°C	21.1	22.0	23.1	18.4	15.7	12.5	12.1	11.9	13.8	14.0	16.9	15.2
Avge indoor temp.	P5	°C	22.1	22.1	22.1	22.1	20.3	20.3	20.3	20.3	20.3	20.3	22.1	22.1
Ambient air temp.	P6	°C	20.3	21.6	20.7	15.3	12.6	9.7	10.7	11.4	14.1	13.8	15.3	17.8
Solar fraction	P21	-	0.66	0.65	0.57	0.48	0.37	0.33	0.35	0.43	0.51	0.53	0.64	0.65
Irrigation	P102	L/day	124	111	74	49	25	0	0	0	0	25	49	99
Cooling duration	P110	min	36	18	0	0	0	0	0	0	0	0	0	18
Heating duration	P131	min	0	0	32	106	222	328	360	303	201	127	85	0

4.3.7. Model calibration and verification

Model results were calibrated against measured water, electricity and gas use as well as utility modelled wastewater flows. There was a stronger focus on calibrating modelled water and gas use inputs due to the availability of more robust water and gas use datasets for verification.

Initial model results under-predicted regional water use, wastewater flow and gas use for most of the year, whilst both water and electricity use were over-predicted during the summer period. The model was calibrated to the utility data increasing the rate of evaporative cooling to reduce modelled water and electricity use during summer. Tap use (hand washing, teeth brushing, shaving, and toilet flushing) was increased in the model to resolve the general under-prediction of water consumption and wastewater flow throughout the year. Rate of garden irrigation within the model were also increased and resolved the over-prediction during summer. Lastly, the under-prediction of gas use throughout the entire year was calibrated through modifying parameters related to cooking use, and under-prediction of gas use during the cooler months was resolved by increasing space heating.

Once the model was calibrated and verified, the root mean squared error was used to quantify how accurately the model fit the measured water use, wastewater flow, electricity and gas use data whilst the mean absolute percentage error was used to quantify uncertainty in predicted water use, WRE-electricity use and WRE-gas use.

4.3.8. Scenario analysis

This study focused on the regional scale modelling of the current and long-term effects of water utility actions on residential water use, WRE use and WRE-GHGs. The actions committed to by Melbourne water utilities that have been used for scenario analysis in this study were: (i) to increase water savings at home through increased penetration of water efficient shower heads and water efficient clothes washers, and (ii) to minimise current and future GHG emissions through implementing water conservations measures (e.g. increased penetration of water efficient shower heads and clothes washers). The current effects of water utility actions were evaluated through scenarios S1, S3 and S5 whilst the associated behaviour change scenarios i.e. decisions made by the householder were evaluated through scenarios S2, S4 and S6 (Table 4-8). Scenario S5 was included as the alternative option to scenario S3. The long-term effects of water utility actions were evaluated through scenario S7 which used the predicted changes in the number of households for each household composition to re-evaluate scenarios S1-S6 in the year 2031.

The number of Reservoir households is predicted to increase by 33.3% between 2013 to 2031 whilst the population is predicted to increase by 31.6% (Figure 4-2). The population projection has considered local level projections of future land use, dwelling capacity and local demographic factors [203].

Table 4-8: Scenario descriptions for assessment of potential water and energy savings.

Baseline model			
S0	2013 baseline model		
Technology change scenarios		**Associated behaviour change scenarios**	
S1	100% penetration of efficient shower heads	**S2**	S1 + 100% switch to low shower duration
S3	100% penetration of front loaders	**S4**	S3 + 100% switch to cold wash cycle
S5	100% penetration of top loaders	**S6**	S5 + 100% switch to cold wash cycle
Future demand scenario			
S7	2031 predicted future demand model for S0-S6 based on predicted changes in demographics		

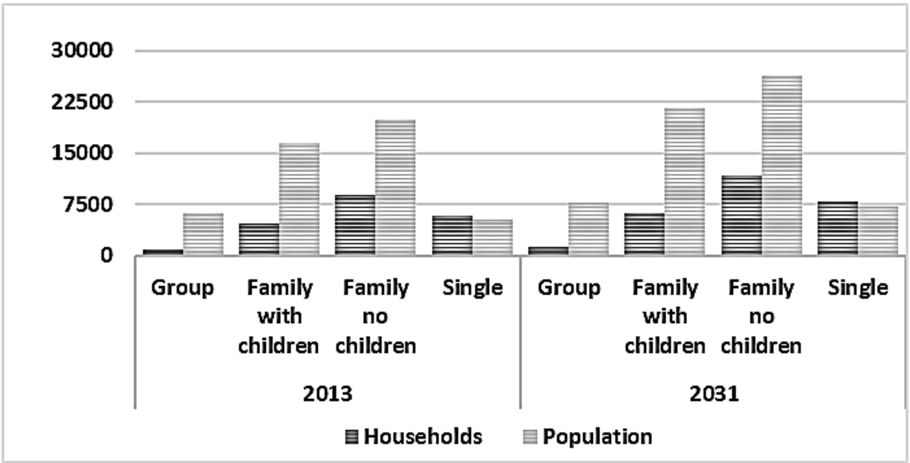

Figure 4-2: Predicted changes in households and population for each household composition type.

4.4. Results

4.4.1. Regional model calibration and verification

Monthly predictions of water and WRE agreed with measured values between 4-8%. Mean absolute percentage errors in predictions in decreasing order of model fit were: gas use, 4%, water use, 7%, electricity use 8%, and wastewater flow 20% (Figure 4-3 (a-d)).

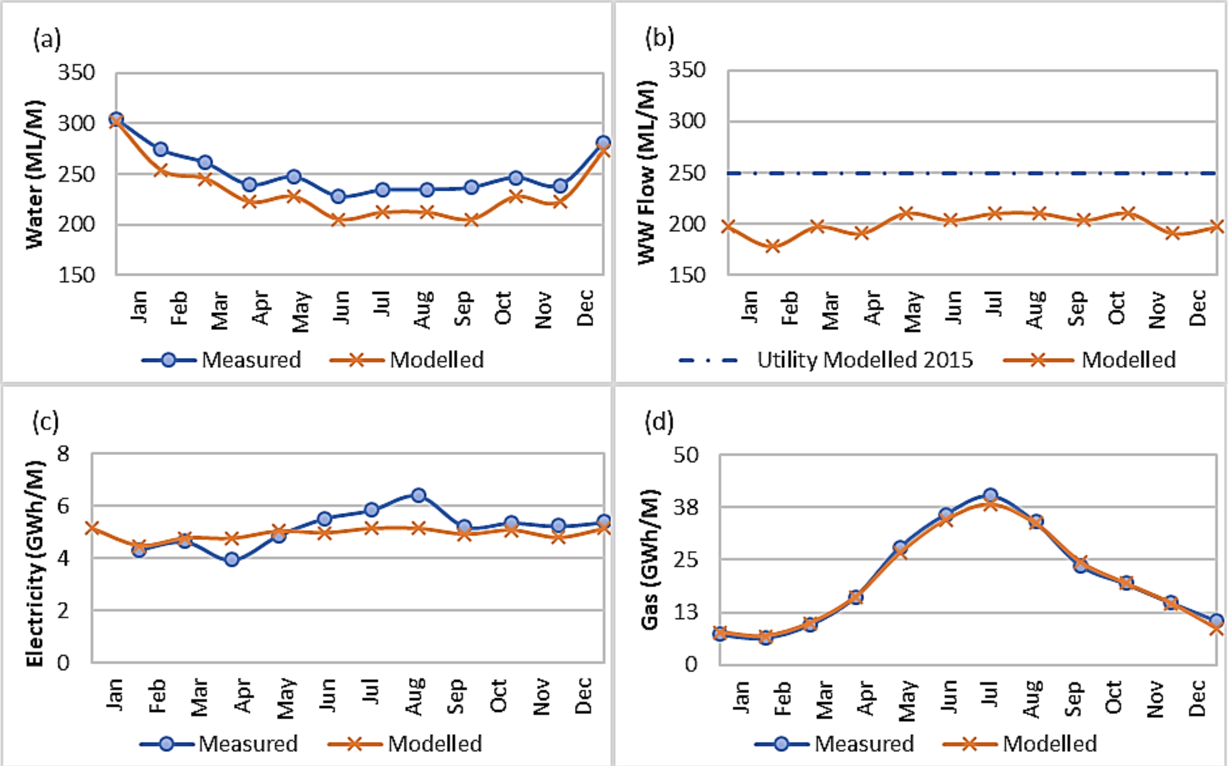

Figure 4-3: Regional ResWE model outputs compared with measured and utility modelled data for Reservoir's residential (a) water use, (b) wastewater flow, (c) electricity, and (d) gas use during 2013.

The root mean square error followed a similar pattern, and for gas use, water use, electricity use, and wastewater flow were 1 GWh, 19 ML, 1.6 GWh, and 50 ML, respectively. The greatest error in model prediction was for wastewater (Figure 4-3 (d)), however, further calibration of wastewater flows was limited as there was no available measured wastewater data, only water utility modelled wastewater flows which were predominantly for 2015 instead of 2013. Furthermore, model prediction outside of the temporal scope of the study has not been verified, for example, electricity use data for 2014 produced a root mean square error of 2.1 GWh, an additional 10% error in electricity use estimates above 2013 results.

4.4.2. Factors affecting household consumption

The ResWE model predicted that across all 320 household types, shower duration and shower head efficiency had the biggest impact on WRE. The 16 shower use and clothes washing configurations were then divided into four quartiles based on WRE: 'low', 'moderate', 'high' and 'very high' WRE were defined as the households corresponding to the first, second, third and fourth quartile of WRE use. The lowest WRE use was predicted for households with a short shower duration, most of which were modelled with efficient shower heads (Figure 4-4 (a), see Appendix D.5, Table D-12 for a summary of results). Notably, there were no households modelled with a long shower duration that resulted in low WRE. The 'moderate' WRE use households consumed on average 25-40% (0.5-0.7 kWh/p.d) more WRE than low energy households. This group had the most diverse household types, modelled mostly with short showers and a mix of efficient and inefficient shower heads (Figure 4-4 (b)). Households with 'high' WRE use consumed on average 53-83% (0.9-1.4 kWh/p.d) more WRE than low energy households. These households were mostly modelled with efficient shower heads and long showers (Figure 4-4 (c)). The highest WRE use households consumed on average 103-189% (1.8-2.8 kWh/p.d) more WRE than low energy households and were modelled with inefficient shower heads and long showers (Figure 4-4 (d)). Greater variability from low to very high WRE use was observed in households with higher adult occupancy rates whilst single person dwellings consumed the most WRE per capita.

WRE was high regardless of the other factors if clothes were washed in warm water for a top loader clothes washer. Households with a top loader warm wash cycle used at least 50% more energy than the lowest energy households (Figure 4-4, Table D-12). Thus, low WRE use could not be achieved in households using a top loader warm wash cycle. Front loaders use less water but more energy than top loaders on cold wash. However, the largest water and energy usage of all was for top loaders on a warm wash cycle.

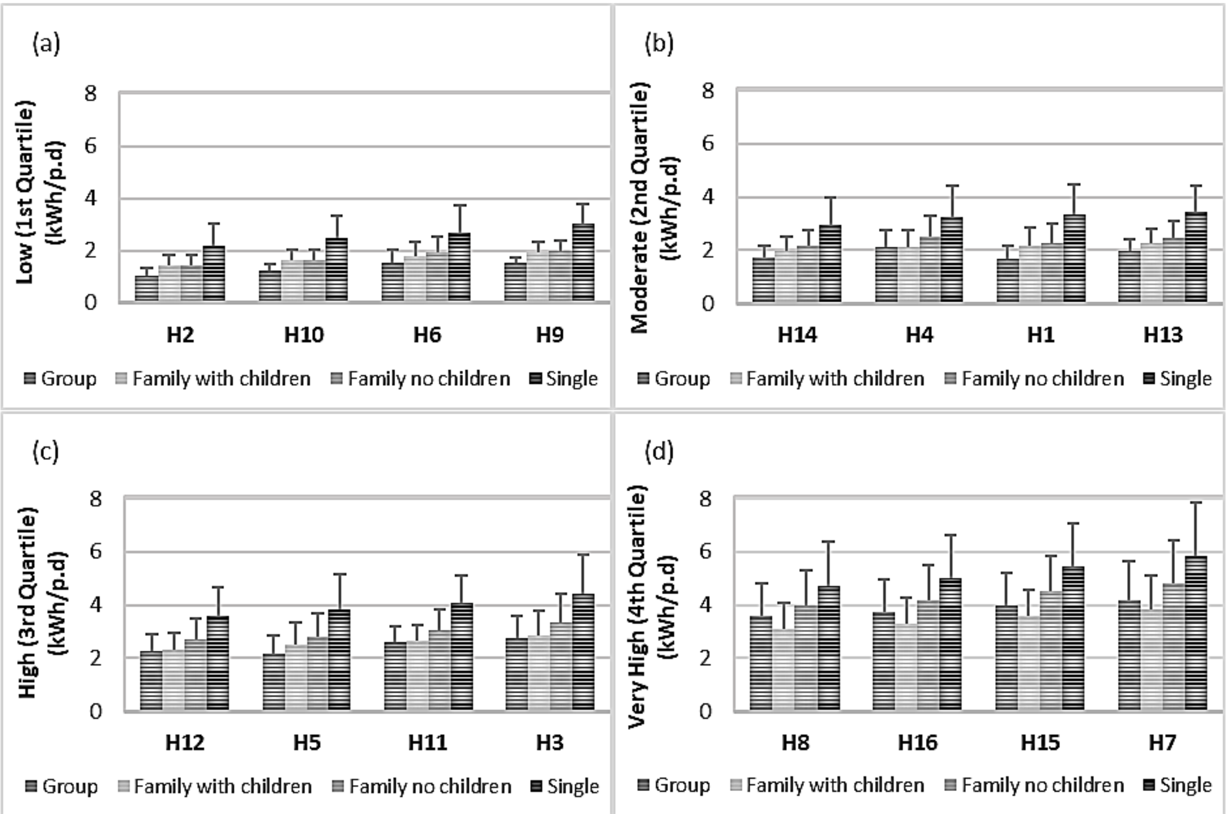

Figure 4-4: (a) low, (b) moderate, (c) high, and (d) very high WRE use impact of household types (i.e. based on shower use and clothes washing) for different household compositions.

Household composition could determine which HWS type minimises WRE. Medium sized HWSs were evaluated for each household composition through the 16 household subtypes that capture shower use and clothes washing variability. The ResWE model predicted that WRE use was lowest in all households that used electric-boosted and gas-boosted SHWS (Figure 4-5 (a)). However, when solar systems were not used, group households and family households (with children and without children) consumed the least amount of WRE use per person per day with electric storage systems (2.6 ±1.0, 2.8 ±0.7 and 3.3 ±1.1 kwh/p.d, respectively) whilst single occupancy households were the only household composition that benefited from using a continuous gas system (4.5 ±1.7 kwh/p.d) over electric or gas storage. Consequently, household composition (encompassing shower use and clothes washing use variability) was a key factor in determining which non-solar HWS type would minimise household WRE use.

In contrast to the HWS impact on WRE use, related GHGs were lowest for all households using gas systems compared with households using electric systems (Figure 4-5 (b)). GHGs for electric systems (solar and non-solar) were significantly higher (2-5 times) than gas systems. Single occupancy households still benefited from using a continuous gas system (1.0 $kgCO_{2-e}$/p.d). However, group households and family households (with and without children) produced the least amount of GHGs per person per day with either gas storage or continuous gas systems (0.7, 0.7, and 0.8 $kgCO_{2-e}$/p.d, respectively) when gas-boosted solar systems were not used. More importantly, the household composition is not a factor in determining the WRE-GHGs of HWSs.

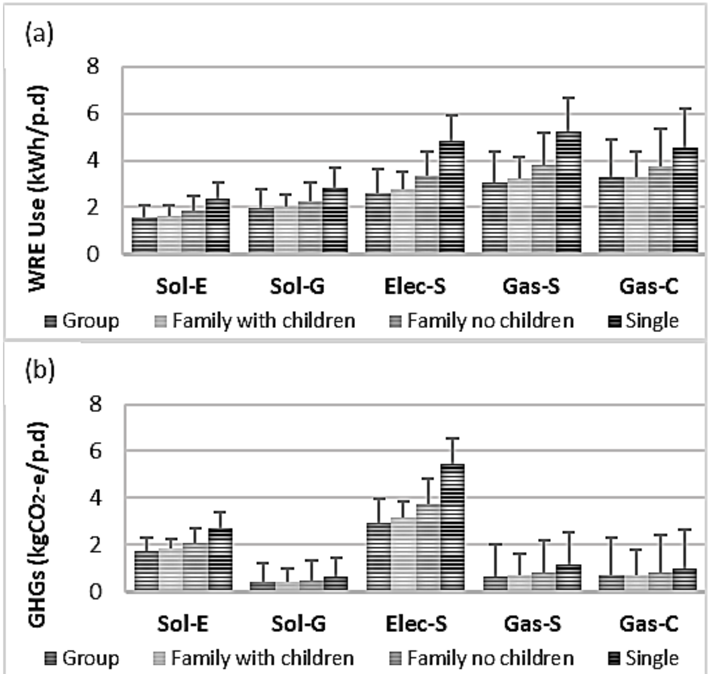

Figure 4-5: Impact of HWS types on (a) WRE, and (b) GHGs, for each household composition type.

4.4.3. Impact of scenarios on regional consumption

Across the six technology and behaviour change scenarios, the regional ResWE model predicted that increasing efficient shower head penetration and reducing shower duration (S2) would cause the greatest reductions in water, WRE and associated GHGs across the study site. Scenario 2 provided an estimated annual water reduction of 27% (0.8 GL/yr), WRE-electricity reduction of 15% (2.3 GWh/yr), WRE-gas reduction of 48% (23.9 GWh/yr), and WRE-GHG reduction of 28% (7.8 $ktCO_{2-e}$/yr) under current demographics (Figure 4-6 (a-h)). Excluding behaviour change, the next largest potential reduction in water, WRE-gas and WRE-GHGs came from installing efficient shower heads alone (S1) which gave an estimated annual water reduction of 17% (0.5 GL/yr), WRE-gas reduction of 29% (14.5 GWh/yr), and WRE-GHG reduction of 17% (4.7 $ktCO_{2-e}$/yr). Conversely, this was not the case for WRE electricity use, where the second largest reduction in regional WRE-electricity use by 10-14% (1.5-2 GWh/yr) resulted from increasing the penetration of top loader clothes washers.

Changes in the penetration of front loader clothes washers compared with top loader clothes washers had a mixed impact on annual water use, WRE and associated GHGs. Replacing top loader clothes washers with front loaders reduced annual water use by 7% (0.2 GL/yr) whilst the reverse increased annual water use by 3% (0.1 GL/yr). From a water utility perspective, increasing the penetration of front loaders would minimise regional water use. However, this is not the case for regional WRE-GHGs. 100% penetration of front loader clothes washers reduced Reservoir's overall WRE footprint by 1-3% (0.3-2.2 GWh/yr) but increased WRE-GHGs by 3-11% (0.9-3 $ktCO_{2-e}$/yr) due to the increased reliance on the electricity grid. Alternatively, 100% penetration of top loader clothes washers increased Reservoir's overall WRE footprint by 0.2% (0.2 GWh/yr) when both cold and warm wash cycles were used but also reduced the WRE footprint by 9% (5.7 GWh/yr) when only a cold wash cycle was used. Regardless of the top loader wash cycle temperature, there was still an overall reduction of WRE-GHGs by 5-11% (1.3-3.1 $ktCO_{2-e}$/yr). Consequently, front loader clothes washers reduced regional water use at the unexpected cost of increasing regional WRE-GHGs whilst top loader clothes washers increased regional water use but reduced regional WRE-GHGs.

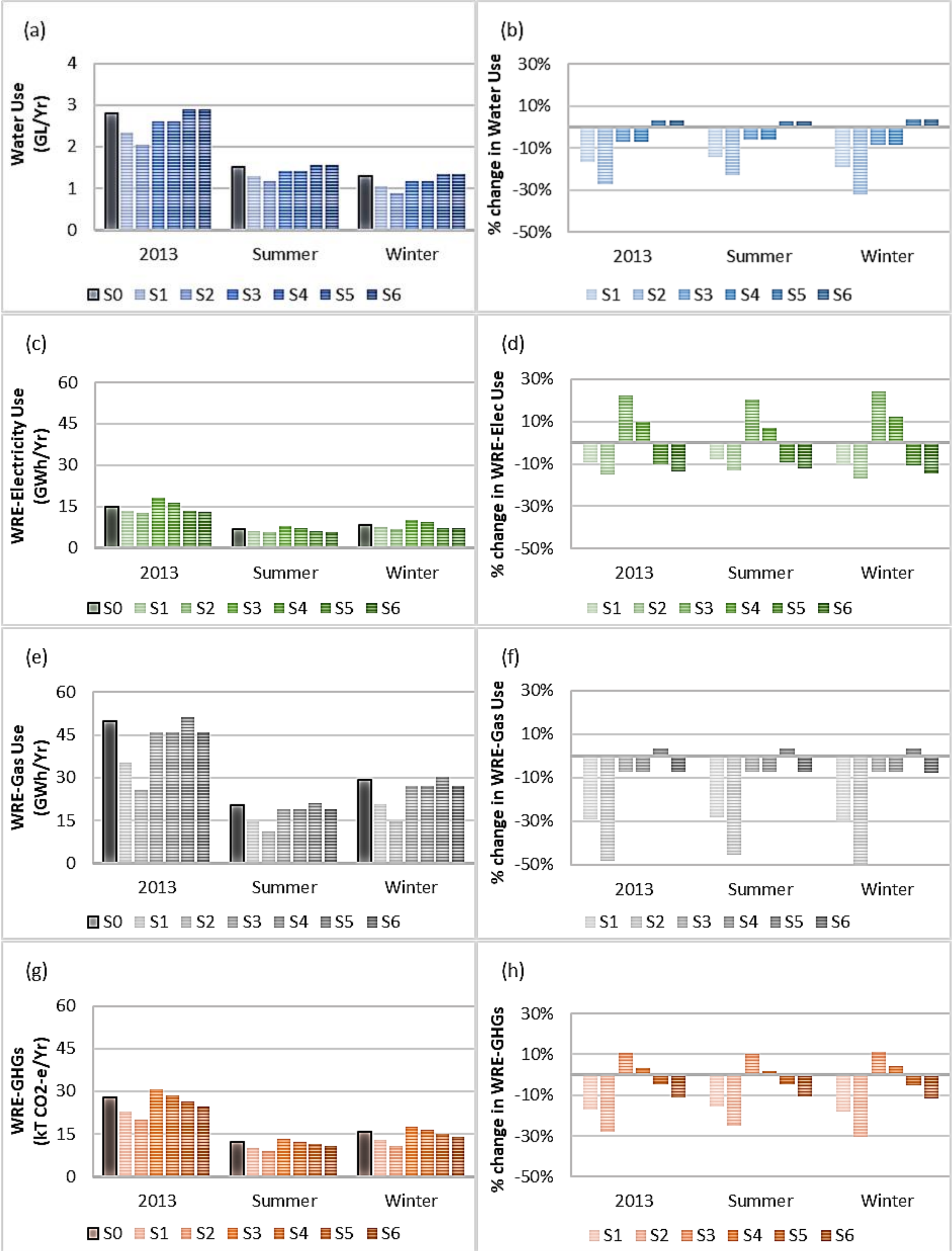

Figure 4-6: Regional ResWE baseline model (S0) and scenarios (S1-S6) results for 2013 annual and seasonal changes in (a-b) water use, (c-d) WRE-electricity use, (e-f) WRE-gas use, and (g-h) WRE-GHGs.

Across the four household compositions evaluated in this study, families without children were the largest consumers, ≈43% of regional water, WRE-electricity, WRE-gas and WRE-GHGS (Figure 4-

7). This was followed by families with children households (≈30%), single households (≈16%), and group households (≈11%). Both families without children and single households were the smallest households per capita (i.e. % household > % population) out of the four household composition types and were the highest consumers per capita. Concurrently, families with children and group households were the largest households per capita (i.e. % household < % population) and were the lowest consumers per capita.

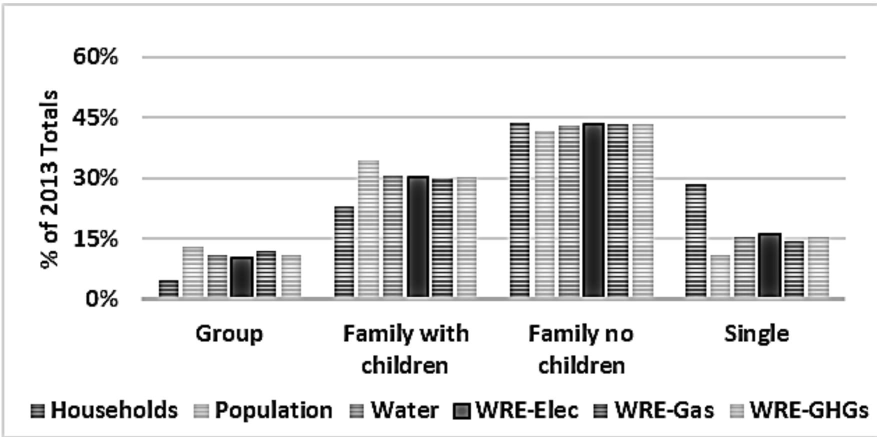

Figure 4-7: Demographic impact on regional water, WRE and associated GHGs for Reservoir, 2013.

Temporal trends: Water use was lowest in winter, whereas WRE use was lowest in summer (Figure 4-6 (a-h)). Overall water use (i.e. indoor and outdoor) was higher during summer than winter, however, indoor water use was a higher proportion of overall water use during winter (i.e. low irrigation rates during winter). Understandably, when technology and behaviour changes were implemented (i.e. changes to end uses affecting indoor water use only), they had a smaller impact on summer water use than winter water use. Conversely, WRE use and associated emissions were predicted to be lower during summer than winter, due to shorter shower times, smaller clothes washing volumes, warmer temperatures (e.g. ambient air temperature) which reduced HWS efficiency losses and the higher SHWS fractions during summer also reduced the reliance on gas and electricity. As a result, water conservation behaviours and technologies (e.g. S1-S6) were predicted to generate lower WRE and WRE-GHG savings in summer than winter.

4.4.4. Impact of scenarios on projected regional consumption

The expected 32% population increase and 33% increase in number of households over the next 20 years is predicted to cause a 32% (0.9 GL/yr) increase in water, 31% (4.6 GWh/yr) increase in WRE-electricity, 32% (16.1 GWh/yr) increase in WRE-gas, and 31% (8.7 kt$CO_{2\text{-}e}$/yr) increase in WRE-GHGs under current conditions (Figure 4-8). The predicted population increase went through a change of household types with a rise in single households which use the most resources per capita whilst there was a slight decline in all other household types. However, family households (with and without children) which use less resources per capita than single dwellings were still the dominant household type. Despite the predicted population rise, 100% uptake of water efficient shower heads and 4-minute showers would completely offset the effects of demographic change. Water use declines from the business as usual scenario by 35% (1 GL/yr), and WRE-gas use declines by 63% (31.5 GWh/yr). While WRE-electricity was higher than 2013 conditions, WRE-electricity declines from business as usual projections by 19% (2.9 GWh/yr), and WRE-GHGs reduced by 36% (10.1 $ktCO_{2\text{-}e}$/yr).

The clothes washing technology and behaviour change scenarios for the forecasted demographic change, led to contrary outcomes for regional water, WRE and associated GHGs. Encouraging all householders in Reservoir to switch to a front loader clothes washer predicted a decline in water demand from business as usual by 9% (0.3 GL/yr) and a decline in WRE-gas demand by 10% (4.7 GWh/yr) (Figure 4-8). Adversely, the implementation of front loaders across Reservoir also predicted a further increase in WRE-electricity demand and WRE-GHGs from business as usual results by 13-30% (2-4.5 GWh/yr) and 5-15% (1.3-4 $ktCO_{2\text{-}e}$/yr), respectively. Alternatively, a 100% uptake of top loader clothes washers predicted only a minor increase in regional water demand and WRE-gas demand from current conditions by 5% (0.1 GL/yr, 2.4 GWh/yr), if householders maintained the current mix of warm wash and cold wash cycle preferences. However, a 10% (4.8 GWh/yr) reduction in regional WRE-gas demand from the business as usual scenario was predicted if all householders switched to a cold wash cycle. Additionally, predicted WRE-electricity demand and WRE-GHGS were lower than current conditions by 13-17% (1.9-2.6 GWh/yr) and 6-14% (1.7-4 $ktCO_{2\text{-}e}$/yr).

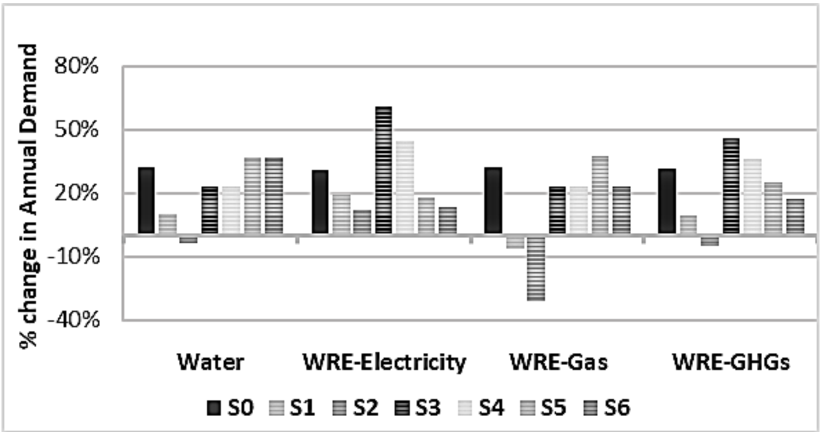

Figure 4-8: Predicted water demand, WRE-electricity demand, WRE-gas demand and WRE-GHGS using regional ResWE baseline model (S0) and scenarios (S1-S6) results for predicted population change in 2031 (S7).

4.5. Discussion

4.5.1. Implications for household WRE

Shower systems offered the most substantial lever for reducing both water and associated energy consumption, under current and future conditions but involved both technology and behaviour change. Most importantly, in high WRE use households, efficient shower heads weren't enough to reduce WRE use when long showers were taken thus shower head rebates alone without behaviour change would not be enough to minimise WRE use. Under the six scenarios considered in this study for four key determinants of residential water and WRE consumption (household composition, HWS type, shower use, and clothes washing use), there was only one scenario in which population increase and demographic change could be offset by changes in household activities. In that case, both technology and behaviour change were needed: efficient shower head, and reduced shower duration. The willingness of such changes would need to be established with the impacted community.

Changes in household end use behaviour had a greater impact on household WRE than changes in household end use technology. A switch from a long shower duration to a short shower duration (i.e. change in shower use behaviour) reduced household WRE by 50% for efficient shower head households and by 90% for inefficient shower head households in low energy use households (see Table D-12). Whereas a switch from inefficient shower heads to efficient shower heads (i.e. change in shower use technology) reduced household WRE by 20% for short shower duration households and 65% for long shower duration households. Changes in behaviour were also the major lever for water and WRE conservation associated with clothes washing. A switch from a warm wash cycle to a cold wash cycle (i.e. change in clothes washing behaviour) was predicted to reduce household WRE by 50% for top loaders and by 20% for front loaders in low energy use households. Whilst a switch from using a top loader clothes washer to a front loader (i.e. change in clothes washing technology) had less impact, and reduced household WRE by 15% for warm wash cycle households and conversely increased WRE by 10% for cold wash cycle households.

Economies of scale mean that reducing WRE may require different technologies in different households. In all households, SHWSs result in the lowest WRE consumption. However, when comparing gas storage, electric storage and gas continuous systems, the household composition determined which HWS had the lowest WRE per capita and per household. Single households were the only case in which gas continuous was the most energy efficient choice. WRE for single dwellings with a gas continuous system was 6-14% lower than the same household with either an electric storage or gas storage system. Larger households had the lowest WRE when electric storage was used, rather than gas storage or gas continuous systems. For instance, WRE from using electric storage systems instead of gas systems was lower by 16-22% for group households, 14-16% for family with children households, and 12-13% for family without children households. However, electric storage systems produced a significantly larger amount of WRE-GHGs than non-solar gas systems (+340% group households, +350% family with children households, +355% family without children households, and +380% single households). The results demonstrate the trade-offs between WRE use and associated GHGs for each HWS and household composition type.

4.5.2. Implications for regional water and WRE management

The clothes washer paradox demonstrates how the combination of technology and behaviour affect water and WRE consumption at household and regional scales. In our study site, 69% of households use top loader clothes washers, and 32% wash their clothes in warm water. Guidelines for the development of water supply-demand strategies in this region support initiatives such as increasing the penetration of water efficient clothes washers [204, 205]. Additionally, water utilities are also committed to reducing GHG emissions associated with water supply [206]. However, 34% of GHG emissions associated with residential water supply are due to water heating in households [86]. Switching from a top load to a front load (i.e. water efficient) clothes washer reduces WRE use by 15% for a warm wash cycle, but only 32% of households use a warm wash cycle. Thus, at regional scale, 100% penetration of top loaders increases water consumption by 5%, but has a minimal effect on regional WRE, because top loaders use less energy than front loaders for a cold wash, and most households wash clothes in cold water. While these numbers are specific to the study site, the results suggest that water utility guidelines for increasing the implementation of water-efficient clothes washers is in conflict with water utility guidelines for reducing GHGs associated with water supply. Consequently, the results have much broader implications: the interaction between technology and behaviour which ultimately determines water use, WRE use, and GHGs, needs to be taken into consideration in policy formation at the regional scale.

Economies of scale mean that household size affects water and energy use per capita. Smaller households (i.e. single households and families without children households) were the largest consumers per capita: overall, 53% of the population lived in 72% of households and consumed 59% of available resources. Conversely, larger households (i.e. group households and families with children households) were the lowest consumers per capita, accounting for 47% of the population, but only 28% of the household stock and ≈41% of regional water, WRE-electricity and WRE-gas thus contributing to ≈41% of regional WRE-GHGs. Even though family households (with and without children) were the largest population in the study site, smaller occupancy households presented as the largest consumers per capita indicating greater WRE savings potential from understanding the water-energy interactions of smaller occupancy households.

Projected demographic change impacts is expected to increase regional scale consumption of both water and WRE in two ways: through population growth and increase in the number of smaller occupancy households. The number of people per household in the study region (and in other developed urban areas) are forecast to decrease over time. For example, single households are predicted to increase by 38% (5,800 to 7,976), and families without children by 32% (8,841 to 11,694). Water consumption per person was 55-65% higher in single households and 15-20% higher in families without children households than for either group households or families with children households, when averaged across the different technologies and behaviours considered in this study. Similarly, WRE per person was 50-65% higher in single households and 15-20% higher for families without children than other household types. Thus, regional predictions of water and WRE demand could be larger than expected from population growth alone.

Environmental conditions also affect WRE consumption. Ambient air and CWTs are higher in summer than winter, therefore HWSs require less energy to heat water in summer than winter due to the higher starting temperatures (see Chapter 3). Consequently, if only summer or winter temperature values, or even if annual average temperatures were used for the environmental factors considered in this study, it would affect the prediction of regional WRE consumption and WRE-GHGs.

4.5.3. Research limitations and directions for future work

In absence of any information to otherwise parameterise our model, it was assumed that technology and behaviour were independent. For example, given that 69% of households use top loaders, and 68% wash clothes in cold water, the final model depicted 47% of households as top-loader, cold wash, regardless of what type of HWS or shower head they use, or how many people live in the house. In practice there may be correlations between technology, behaviour and socio-economic factors. Incorporating these relationships would improve the ability of a regional scale model to forecast the impact of demographic changes, and better assess the outcome of water-energy conservation strategies. The key assumption in this study, is that each household composition has the same proportion of HWS types, shower use variations, and clothes washing variations. This approach has been undertaken as data on these relationships is currently not available. To address this, sensitivity testing of the average case could be conducted as a means of quantifying potential variability (ranges) in the analysis results which would then be compared with empirical data.

There were challenges in model parametrisation and verification when using data on different spatial and temporal scales. More robust electricity and wastewater flow data could have resulted in a change of parameters used for model calibration. However, this study focused on calibrating modelled water and gas use data due to the availability of more robust water and gas use datasets.

Household heterogeneity was captured through modelling a conservative upper and lower limit of shower use and clothes washing use behaviours for each demographic group combination with hot water system type. For example, short shower duration was modelled at 4 minutes whilst long shower duration was modelled at 10 minutes. In practice, shorter and longer showers are often taken. Thus, household heterogeneity would capture a range of shower use behaviours outside of the scenarios tested. However, conservative approach to modelling upper and lower limits of end use behaviour choices was taken as a precautionary means to estimating resource use and potential resource use savings. To address this limitation, future work would include a Monte Carlo approach to modelling household heterogeneity in the regional ResWE model. Additionally, scenarios tested assumed a 100% adoption of new technologies and behaviour change. Thus, outcomes in this study encompass the worst and best case scenarios, whilst in practice, solutions to ensuring more efficient resource use would lie somewhere in between. A recommendation for future analyses would be a more conservative approach to scenario testing.

Operational energy was chosen as the focus of this study as frequently the upstream and downstream embedded energy have a relatively small effect when compared with operational WRE. For example, Melbourne water utilities typically use between 0.5-1.5 kWh/hh.d to provide water supply and sewage disposal services for an average water use household of 500 L/hh.d [134] and only a small portion of this would be attributed to each household end use. Comparatively, the operational WRE results from this study demonstrate that WRE use (by HWS type) is 2.6 ±1.0 to 6.1 ±1.0 kWh/p.d. However, it is important to note this study did not include the projected utility WRE savings from the projected reductions in residential water use which would ultimately, yield different results and potentially different policy implications.

4.6. Conclusion

This chapter investigated the combined effects of technology, behaviour and demographics on cumulative consumption of water, WRE and associated production of GHG emissions in urban water systems. By establishing a regional scale model, the research makes novel contributions including the: (i) simultaneous analysis of numerous households using high-resolution, bottom-up data, (ii) evaluation of WRE consumption at household and regional scales, and (iii) detailed assessment of scenarios of changes in technology, behaviour and demographics on water, WRE and associated GHG emissions. The key conclusions of this chapter include:

- Changes in household end use behaviour had a greater impact on household WRE than changes in household end use technology, for example, changes in shower use behaviour reduced WRE by 50-90% whilst changing shower use technology reduced WRE by 20-65% in low energy use households.
- Shower systems offered the most substantial lever for reducing both water and associated energy consumption but involved both technology and behaviour change. There was an estimated annual water reduction of 27% (0.8 GL/yr), WRE-electricity reduction of 15% (2.3 GWh/yr), WRE-gas reduction of 48% (23.9 GWh/yr), and WRE-GHG reduction of 28% (7.8 $ktCO_{2\text{-}e}$/yr) from implementing efficient shower heads and householders committing to a 4 minute shower duration.
- The clothes washing paradox emphasized the need to consider the interactions between technology and behaviour in policy formation at the regional scale. Front loaders (i.e. water efficient clothes washers) reduced household WRE by 15% for a warm wash cycle but only 32% of households used warm water. Thus, at regional scale, increasing the penetration of top loaders had the least impact on regional resources because top loaders used less energy than front loaders for a cold wash, and 68% households washed clothes in cold water.
- HWS technology had different impacts on WRE consumption in different household composition types. Single households had lower WRE from gas continuous systems, reducing WRE by 6-14%, whilst all other household compositions had lower WRE from electric storage systems, reducing WRE by 16-22% for group households, 14-16% for family with children households, and 12-13% for families without children households. In contrast, WRE-GHGs for electric storage and electric-boosted solar systems were significantly higher than gas HWSs.
- Household composition was a significant factor in more efficient regional water and energy consumption. Smaller households were the largest consumers per capita where a combined 53% of the population lived in 73% of households and consumed 59% of resources. Conversely, larger households were the lowest consumers per capita where 47% of the population lived in 27% of the household stock and consumed 41% of resources.

In summary, the following recommendations for reducing WRE use in residential urban water systems. The policy level recommendation is the investigation into combined policies for simultaneously achieving water efficient, WRE efficient and GHG reduction mandates. Additional information on combined water and energy efficiencies of applicable household appliances is also recommended. Water utility level recommendation is the inclusion of resource use for different demographic groups in predictive models (e.g. a key result from this study was the higher per capita usage of smaller occupancy households and the projected increase of smaller occupancy households in future populations). Household level recommendation is the increased adoption of water efficient showerheads but a careful consideration of water efficient clothes washers in line with clothes washing temperature preferences (i.e. warm wash households can adopt water efficient clothes washers but cold wash households would increase their WRE use in doing so). Individual level recommendation is the increased awareness that choices in end use behaviour have a greatest impact on resource use. This means that all individuals, regardless of demographics or the ability to upgrade to water efficient appliances, would be able to substantially reduce their WRE footprint by taking shorter showers and where possible, reducing hot water usage by switching to cold wash clothes washing.

Collectively, the results demonstrated that scenarios of change can have quite varied impacts on water, WRE and associated GHGs, results which could not be predicted from a standard top-down or bottom-up modelling approach. The work moves the understanding of WRE well beyond the much more common presentation of results averaged over space, time and households.

Chapter 5. Integrating Top-Down and Bottom-Up Information to Improve Prediction of Urban Water-Related Energy

This chapter addresses the third research objective (RO) and research question (RQ) of this thesis:

RO 3: Propose how to integrate information from water and residential sectors to reduce WRE.

> ***RQ 3: How can information be integrated across the spatial and temporal scales needed to reduce WRE use across the residential and water sectors?***

Based on key research outcomes from RO 1 and RO 2, this chapter proposed the concept of integrating information from water utility and residential sectors to reduce WRE use across utility and household scales. This was done by:

- Reviewing spatial and temporal scales for data collection and availability, reviewing approaches to WRE quantification from top-down and bottom-up data, and reviewing limitations to integrating WRE information.
- Proposing a platform to integrate top-down data and bottom-up data from current WRE modelling methods and decisions across scales through reviewing previous studies in closely related fields.

5.1. Abstract

The need to investigate and quantify water-energy interactions to efficiently co-manage water and energy resources is widely recognised and is growing. Higher resolution spatiotemporal modelling of water-energy interactions can provide insights into improving efficient and/or resilient urban water systems, and related energy. A conceptual water-related energy (WRE) model is proposed to couple the regional scale ResWE model of residential water-energy interactions to a geographical information system (GIS) platform. This improves analysis of WRE data across utility and household scales. The proposed conceptual model integrates top-down and bottom-up data over a range of spatial and temporal scales to evaluate the cumulative impacts of changes in factors that influence WRE use. The intended outcome for the conceptual model is to identify residential water and energy conservation opportunities and potential impacts on supporting infrastructure by investigating the connections between utility decisions and residential end use decisions.

5.2. Introduction

Water use, energy consumption and greenhouse gas (GHG) emissions are strongly interconnected [21-23, 46]. Water systems use energy, energy systems use water, and both energy and water systems contribute to GHG emissions [18, 22, 24, 43]. Managing water or energy resources without accounting for these connections can lead to unexpected costs and risks [18, 21, 25, 26]. For example, installing new climate-independent sources of water (e.g. desalination) has increased energy consumption in the Australian water sector and consequently increased costs for utilities and consumers [19, 26, 30]. Energy use is seldom considered in water resource management [21, 31, 32], which is problematic because higher energy demand in the water sector will translate into increased energy costs and related GHG emissions for utilities and consumers [56].

WRE consumption occurs in two distinct arenas: water utilities and end use. Water utilities bear the costs for the energy use associated with water supply [207] and sewage disposal services treatment [29, 43, 44]. End users pay for the energy use associated with water use [2, 45]. The consumption of WRE by utilities and end users is interconnected through water infrastructure design, climate impacts, water appliance technology, end use behaviour, and policies. Integrated water and energy management is needed, to improve the efficiency of water and energy use without problem-shifting between water and energy [37, 41, 42, 208]. For instance, urban water demand management programs can affect WRE consumption (utility and end user) [2, 48, 49, 51]. Furthermore, residential WRE consumption will depend on decisions made at utility and end user scales. Therefore, understanding how end users affect water and energy demand is important [50, 52, 53] for both water and energy utilities.

Two common approaches to quantifying residential WRE are to use either top-down and bottom-up data, each of which has different advantages and limitations. Top-down data provides the most accurate overview of resource use [23, 57] but does not explain how the structural, technological, behavioural or environmental factors influence WRE consumption. It also fails to describe the impact of, site-specific variability (e.g. in environmental factors such as cold water temperature (CWT), or behavioural factors, such as uptake of water efficient technologies). At best, top-down data can provide a rough estimate for potential WRE savings, without identifying the most effective methods to achieve reductions in WRE. Conversely, small scale residential WRE studies collect bottom-up data and can be useful in identifying key factors controlling household WRE consumption e.g. hot water system (HWS) type, shower use, clothes washing etc. [48, 68, 69, 80]. However, these studies do not occur at a scale of analysis that could robustly inform policy decisions such as the implementation of competing rebate schemes. Moreover, the detailed information attained from bottom-up studies can be difficult to scale-up as behavioural characteristics for each household can be quite diverse [122] and have a very large impact on WRE use [72, 78].

Since both approaches provide useful but incomplete information, integrating information from both top-down and bottom-up sources would be useful for quantifying residential WRE use, and evaluating large scale impacts of changes to water infrastructure design, climate conditions, water appliance technology, end use behaviour, and policies from a systems perspective. Synthesizing bottom-up and top-down data requires integration of information over a range of spatial and temporal scales. Spatial variability of residential WRE use is complex and impacts supporting water, wastewater, electricity and gas infrastructure [25]. Additionally, residential WRE use varies in time as a response to peak water demands as well as seasonal changes in water end use which further influences water-energy infrastructure.

This chapter identifies the need for spatiotemporal WRE models which can be applied over large urban areas to assess and predict the impact of demographic changes, technology changes, and water demand/supply side management impacts, on large scale urban WRE consumption and future demand. Spatiotemporal WRE models are needed to: (i) connect decision making processes that occur at different scales e.g. utility decisions on infrastructure management of water supply vs individual decisions on end uses, (ii) assess the impact of and hence prioritise various schemes to reduce water and/or energy consumption, and (iii) forecast future residential WRE demand. This work suggests WRE decisions made at different scales i.e. top-down and bottom-up approaches to

WRE modelling, can be connected through a specified time-frame and geography. It is proposed that spatiotemporal modelling of residential WRE consumption and future demand in a GIS framework would improve the ability to identify and analyse water-energy connections across the utility and residential boundary interface of the urban water cycle.

A new WRE modelling approach is proposed to identify residential water and energy conservation opportunities and the potential impacts on supporting water and energy infrastructure.

5.3. Spatial and Temporal Scales of Data for Decision Making

WRE consumption is affected by decisions made at a range of spatial and temporal scales. Space and time scales at which decisions are made are very different for residents, utilities and government (Table 5-1) , but these decisions are interconnected. For example, at household scale, a resident's decision to install an efficient shower head would impact water use by 5 ML/decade and energy use by 3.7×10^6 MWh/decade because efficient shower heads have an estimated ten year life span (Table 5-1). In contrast at utility scale, the implementation of a shower head rebate scheme would impact water and energy use by several orders of magnitude (7.1×10^2 GL/decade, 5.2×10^8 GWh/decade). This is due to the number of households within the utility boundary that would install an efficient shower head as a result of the utility policy. Additionally, at government scale, new homes must install a minimum 3 star (AAA) efficient shower head (i.e. new home energy efficiency regulations). Thus, government legislation at the state level has a larger impact on water and energy use (2.3×10^3 GL/decade, 1.7×10^9 GWh/decade) due to the larger number of households that would be influenced by this policy. Consequently, the same action conducted by different stakeholders has a significantly varied impact on regional water and energy use.

Determining WRE also depends on the spatial and temporal scales of relevant data. Quantifying WRE use is difficult for a number of reasons. Firstly, whereas water and energy use are measured directly, WRE is not routinely measured, but rather inferred from water and energy use. This makes it difficult to assess or validate WRE consumption at either household or at regional scale [31, 57]. Furthermore, water and energy data is often unavailable [28, 31, 43], out-of-date or misaligned, due to: (i) incongruous data collection boundaries, and (ii) differing spatial and temporal scales of available data [31, 57].

Table 5-1: Spatial and temporal impact on urban water and WRE from data at different scales, using shower use as an example.

Stakeholder	Action	Scale of Influence	Temporal Scale of Influence	Impact on Water Use	Impact on Energy Use
Individual[a]	Shower duration	1 person	5-18 min/day	23-162 L/day	0.5-4.6 kWh/day
Household[a]	Shower duration	1 household	9-60 min/day	38-492 L/day	0.8-14.1 kWh/day
	Efficient shower head[b]	1 household	8.4×10^5 min/decade	5 ML/decade	3.7×10^6 MWh/decade
Utility	Shower head rebate scheme	671,000 households[c,d]	1.2×10^{11} min/decade	7.1×10^2 GL/decade	5.2×10^8 GWh/decade
	Price	671,000 households[c]	5.6×10^{10} min/year	3.4×10^2 GL/year	2.5×10^8 GWh/year
Government	4-minute shower	2,283,000 households[e,f]	1.0×10^{11} min/year	6.0×10^2 GL/year	4.4×10^8 GWh/year
	Building codes: new home energy efficiency	455,000 households[g]	3.8×10^{11} min/decade	2.3×10^3 GL/decade	1.7×10^9 GWh/decade

[a] [98]. [b] Assumed 6 L/min for efficient shower head flowrate [199], Table 7.1. [c] Utility: Yarra Valley Water Ltd [152]. [d] [182], Table 14, assumed 21% uptake. [e] State: Victoria [209], Table 2/2.1 . [f] [181], Table 18, assumed 53% uptake. [g] Assumed net change in projected households equals new builds from 2011-2021 [20].

5.3.1. Incongruous data collection boundaries

There are major challenges to modelling water-energy interactions at the regional scale (i.e. a specified region). Utilities make decisions at the regional scale, but boundaries of water and energy utilities are rarely aligned (Figure 5-1 (a)) [31]. Thus, data on water and energy usage are collected and available at different spatial and temporal scales. For example, the utility administration boundaries for water data (e.g. YVW) and electricity data (e.g. Jemena) used in the case study in Chapter 4 overlapped but were not in alignment (Figure 5-1 (a)).

Additionally, key influences on water and energy use are connected to decisions made at household scale (see Chapter 4). Both technology (e.g. shower heads) and behaviours (e.g. shower duration) affect residential WRE use. It's quite possible that both technology take-up and behaviours are affected by socio-economic factors, such as available income, education or even culture, but these relationships are unknown [4, 78]. While it's not known how demographic factors affect behaviour and technology at household scale, it is quite possible that demographic variability in the population contributes to spatial variability in resource consumption. However, demographic data is collected and available at different spatial and temporal scales to water and energy use data (e.g. SA2 level census data, Figure 5-1 (b)). Consequently, the study site for Chapter 4 was narrowed down to a smaller region that fit within all three overlapping boundaries of water, energy and census data. Each dataset then required pre-processing to align the spatial and temporal scales of the available data for water-energy-census data correlation. Thus, geographically overlapping datasets important to WRE modelling were difficult to integrate.

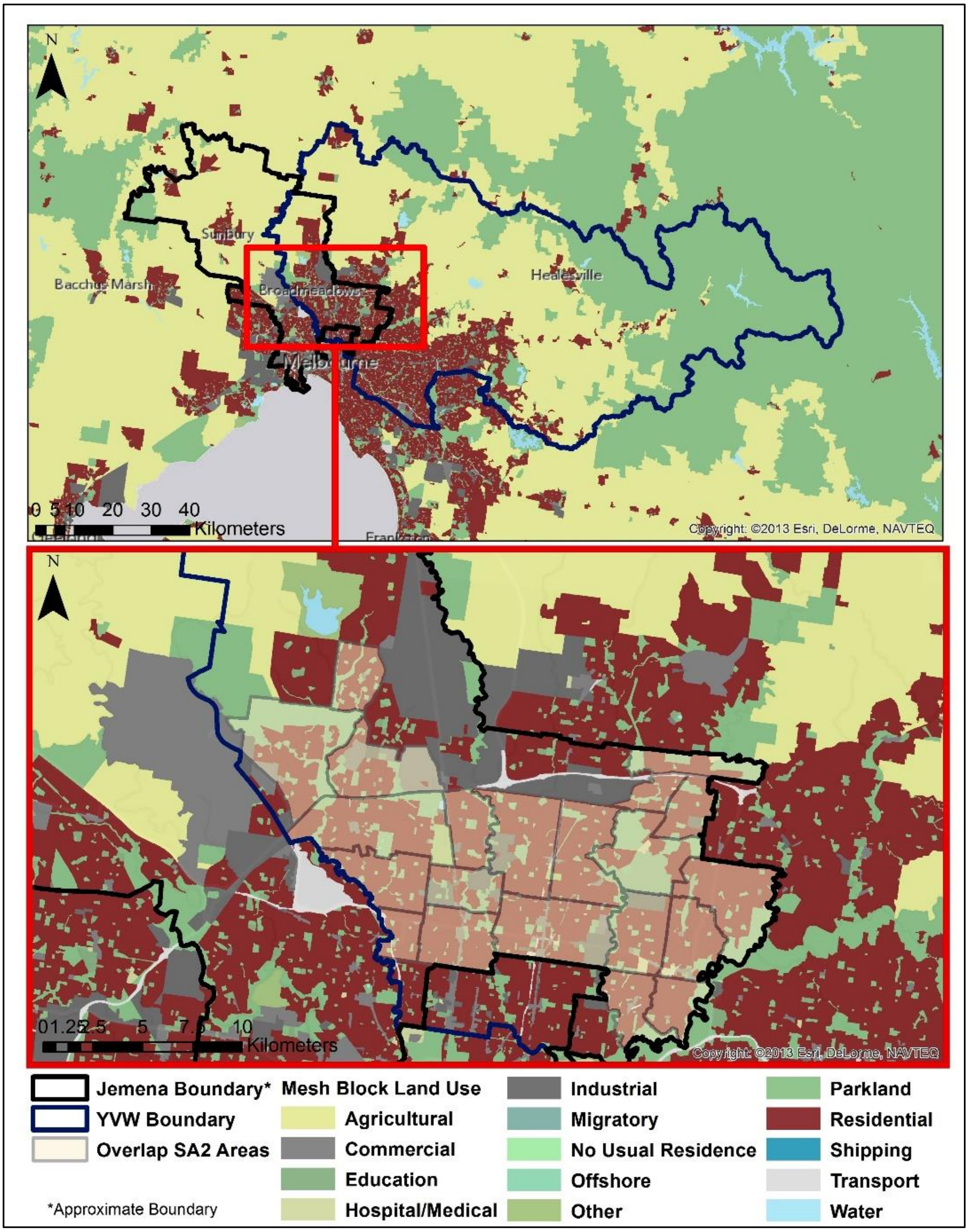

Figure 5-1: (a) Disconnect between boundaries of data collection and availability; (b) Census data (i.e. Overlap SA2 areas) misaligns with the spatiotemporal scales of water and energy data.

5.3.2. Spatial and temporal scales of data availability

Misalignment of spatial and temporal scale of available data limits the investigation of the interconnections between water and energy in the residential sector. For example, the case study in Chapter 4 used empirical water, electricity and gas use data for regional scale model verification, however, the spatial and/or temporal scale issues with each data type presented WRE modelling limitations (Table 5-2). Appendix E presents additional examples of the spatial and temporal scale misalignment of data for the regional ResWE model.

Temporal scale of water use data: Household scale water use data enabled the correlation of water use activities to structural parameters (e.g. land size) however, quarterly water meter readings reduced the ability to characterise water end use events or construct a peak water use profile. This limited the quantification of peak WRE use.

Spatial scale of electricity data: Half hourly electricity meter readings provided peak electricity use profiles however, regional scale electricity data limited the ability to correlate electricity use with household scale water end use events. The model was verified at the regional scale.

Spatial and temporal scales of gas data: Regional scale gas use data provided a gas use profile for the region but impeded the ability to correlate gas use to household scale water end use events. The two monthly gas meter readings provided a seasonal gas use profile (i.e. summer vs winter) which limited household scale gas use model verification.

Table 5-2: Spatial and temporal scales of data availability at the study site (Melbourne, Australia).

Data Type	Spatial Scale	Temporal Scale	Issues	Source
Water use	Household	Quarterly	Temporal scale is large.	[193]
Electricity use	Postcode	Half Hour	Spatial scale is large.	[196]
Gas use	Postcode	Two Month	Spatial and temporal scale are large.	[195]

Available data is tailored for utility decisions on infrastructure management, which limits water-energy data analysis (e.g. investigations into individual decisions on end uses) due to the spatial and temporal resolution differences of each data type [31]. Moreover, the misalignment of datasets limits the predictive capabilities of WRE models. Improved water and energy data would overcome this limitation, increase the understanding of household scale water-energy interactions and assist in identifying feasible technological and/or behaviour opportunities to reducing residential WRE.

5.4. Approaches to Quantifying and Predicting WRE

Modelling and analysis of water-energy interactions is important for understanding and inform decision making in the management of water and energy resources. Currently, there are two major sources of information for quantifying water-energy interactions: (i) top-down and (ii) bottom-up data (Table 5-3). Top-down information is typically applied in large scale studies, to capture the impact of decisions made by utilities and provide the big picture summary on resource use. This approach is easier to use for management decisions because of the scale of analysis. However, these studies do not capture the spatiotemporal variability in the key factors controlling water-energy interactions. The bottom-up approach used in small scale studies, captures end user decisions and highlights the key factors controlling household water-energy interactions. Bottom-up data, however, does not span a scale of analysis that could robustly inform management decisions such as the implementation of competing rebate schemes. Consequently, a new approach, integrating top-down, and bottom-up data is needed to evaluate the WRE impacts of water-energy interactions.

Table 5-3: Summary of advantages and limitations to top-down and bottom-up approaches for quantifying residential water-energy use.

Approach	Studies	Advantages	Limitations
Top-Down (e.g. Input-output; black box modelling)	[23, 27, 57, 59, 65, 86, 210]	▪ Provides the big picture summary of the water-energy nexus either at national, state or city scale. ▪ Aggregate data is more readily available.	▪ Cannot identify the key influences on water-energy interactions. ▪ Does not capture heterogeneity of either technology or behaviour which affects water and WRE consumption.
Bottom-Up (e.g. assess impact of single technology or multiple water end uses)	[44, 48-50, 54, 55, 60, 61, 63, 68, 69, 76-78, 80, 90, 91, 97, 99, 100, 102, 103, 106, 109, 123, 124, 211]	▪ Measures what is actually happening in individual houses and gives some idea of variability between households both of which are important for interpreting top-down information.	▪ Results from household studies are often scaled using a proxy such as population density to represent WRE use in cities, states or nationally. ▪ Does not capture the spatial and temporal patterns of WRE use across large areas.

5.4.1. WRE from top-down data

The top-down approach is used in large scale studies and relies on highly aggregated data [9], for example, data that represents the whole sector of interest [122] used in input-output models. Key studies providing an overview of: WRE for domestic water use at a city scale [86], state scale [65], and national scale [57, 59]; WRE for water treatment, supply [27, 59, 86, 210], and wastewater services [59, 86, 210]; and WRE for water flows [23]. These studies provide an overview of resource use and potential resource savings at the utility, city, state, or national scale. However, these studies cannot be connected to key levers for mitigating WRE use such as the technological or behavioural aspects of end use activities.

5.4.2. WRE from bottom-up data

Bottom-up data is typically collected in small scale studies. Examples of bottom-up data include partial sector input data, and individual data derived from surveys, interviews [122], and end use meters. Key studies that have quantified residential WRE have focused on WRE consumption for more than one water end use. More recent WRE studies have focused on the development of integrated water-energy smart metering to classify real-time end use events [50, 54, 55, 123, 124]. Even though this approach is computationally intensive with further need of method development, these studies showcase potential applications for utilities, regulatory agencies and end users [54, 55, 123]. The majority of WRE studies to date, have focused on the evaluation of energy savings and related GHGs. This has been achieved through evaluating changes in: water appliance technology [44, 48, 49, 68, 69, 77, 80], end use behaviour [48, 68, 69, 77, 80], environmental influences [68, 69, 77, 80, 90], and infrastructure [90]. These studies have highlighted potential levers for mitigating WRE use, however, only a few of these studies have included a significant sample of variability between households [48, 50, 77, 80], which is important for understanding how variability in household scale decisions can inform utility and government decisions related to water and WRE policy formation at larger spatial scales.

5.4.3. Limitations of current approaches

As previously outlined, top-down information provides resource savings at larger scales, whereas bottom-up information provides key levers for resource mitigation but these studies aren’t done at a scale of analysis relevant for decision making. There is a need to capture the spatiotemporal variability of key factors controlling WRE within households across a region. In particular, there is a need to integrate information from top-down and bottom up studies in order to better quantify and predict WRE at utility or larger scales, and how this is affected by changes in infrastructure, environment, behaviour, technology, and policies.

Modelling WRE data across scales i.e. across utility and household infrastructure systems is needed to obtain a whole-of-system reduction in urban WRE. Few studies have determined localised influences on infrastructure connected to water and related energy use [54, 123]. Utility scale and household scale data analysis within a spatiotemporal context is needed. Furthermore, there is a need to model the implications of utility infrastructure management on household WRE use. There is also a need to model the impact of the end use variability between households across a specified region and identify the subsequent implications for utility infrastructure management [25]. More importantly, location specific water and WRE use data is needed for improved water-energy management [17] to achieve system-wide reductions in WRE [39].

Environmental influences such as ambient air temperature, seasonally change across geographic locations, thus, dynamically affecting household WRE use [70, 71]. However, few WRE studies have investigated the spatiotemporal variability of environmental influences [27]. More importantly, studies that predict the environmental impact of changing climate conditions on household WRE are needed [71].

Household behaviour contributing to WRE use varies significantly and is likely to be affected by socio-economic factors. Few WRE studies have identified key end use behaviours controlling WRE use within households. Additionally, there is little information that identifies patterns of water, and WRE use relative to demographic attributes [4, 50, 78]. Identifying consumption patterns of socio-economic groups would provide data for targeted resource conservation awareness campaigns [50, 78]. Further investigation of water-energy consumption patterns of socio-economic groups is needed to investigate end use behaviour contributing to WRE.

Upgrading water appliance technology is a favoured option for WRE mitigation. Few WRE studies have confirmed the mechanism within water appliance technologies that influences household WRE use (e.g. quantifying the WRE use associated with different clothes washing temperatures) [2, 77]. Modelling of mechanisms within water appliance technologies is fundamental to identifying household water-energy interactions [2]. These interactions are important for identifying WRE mitigation options which will determine the spatiotemporal impact of water appliance upgrades on regional resources.

In conclusion, there is a need to integrate the top-down and bottom-up information for the water-energy interactions. This is to further WRE modelling advances in the spatiotemporal assessment of factors that significantly contribute to WRE use such as: interactions between utility and residential infrastructure systems, impacts of climate variability, heterogeneity of end use behaviour and associated socio-economic influences, as well as the key mechanisms within water appliance technologies.

5.5. Integrating WRE Information across Scales & Datasets

A spatial and temporal component to current WRE modelling methods is needed to resolve different scales of data and related decisions. For instance, regional-scale modelling is needed to forecast resource demand prior to the installation of large-scale technologies and infrastructure (such as new water supply or wastewater assets). These decisions are made by utilities using top-down data.

Concurrently, household-scale modelling is needed to forecast the impact of end user decisions (bottom-up data) on residential WRE consumption (e.g. choice of clothes washing temperature). Ultimately, predicting future WRE consumption requires integration of top-down and bottom-up WRE use data to represent decisions made by both water utilities and end users (Figure 5-2). Thus, spatiotemporal modelling of residential WRE across a range of scales could provide information on how to minimise residential WRE consumption across the interface between the water utility and residential sectors.

Spatiotemporal modelling of WRE use has led to the investigation of Geographic Information Systems (GIS) which offers powerful options for storing and simultaneously analysing data at different spatial and temporal scales. They can be used to assess a wide range of varying social, environmental and technological factors across different regions, and over time [212, 213]. A key strength of using a GIS framework for spatiotemporal modelling is the ability to apply multiple regression analysis to evaluate the interactions between nested levels of descriptive features (data inputs) at different spatial and temporal scales [130]. Studies using spatiotemporal methods have mapped and evaluated urban water use for water management [146-148, 214] and urban building energy consumption by end use for energy management [137, 150, 151]. Additionally, spatiotemporal methods have been used to evaluate water and/or energy interactions between infrastructure, environment, behaviour and technology which can be used to inform WRE use.

The proposed integration of top-down and bottom-up data for the spatiotemporal analysis of water-energy interactions is presented in Figure 5-2.

A range of studies demonstrate the spatiotemporal modelling potential of residential water-energy interactions. Spatiotemporal analysis in ArcGIS was used in Chapter 3 of this study to evaluate the spatiotemporal variability in CWT supplied by the water utility and determine its impact on household WRE [70] then compared with an energy density map of water supply and sewage disposal services [134]. This research evaluated an important interaction between the environment, water infrastructure, and residential infrastructure, altogether affecting residential WRE use.

The value of modelling the geographical context of infrastructure has been demonstrated in projects focused on: the location of stormwater harvesting sites [149], urban flood risk assessment [215], urban drinking water quality assessment [216], management of the urban water supply network [217], energy intensity of water supply and sewage disposal services [134-136], location of urban energy supply plants [218], evaluation of district heating potential [219, 220], groundwater balances, and associated energy for extraction [6]. Spatiotemporal studies have also demonstrated the importance of modelling urban interactions in a spatiotemporal context through: urban influences on GHGs [10], and urban metabolism [9, 10, 133].

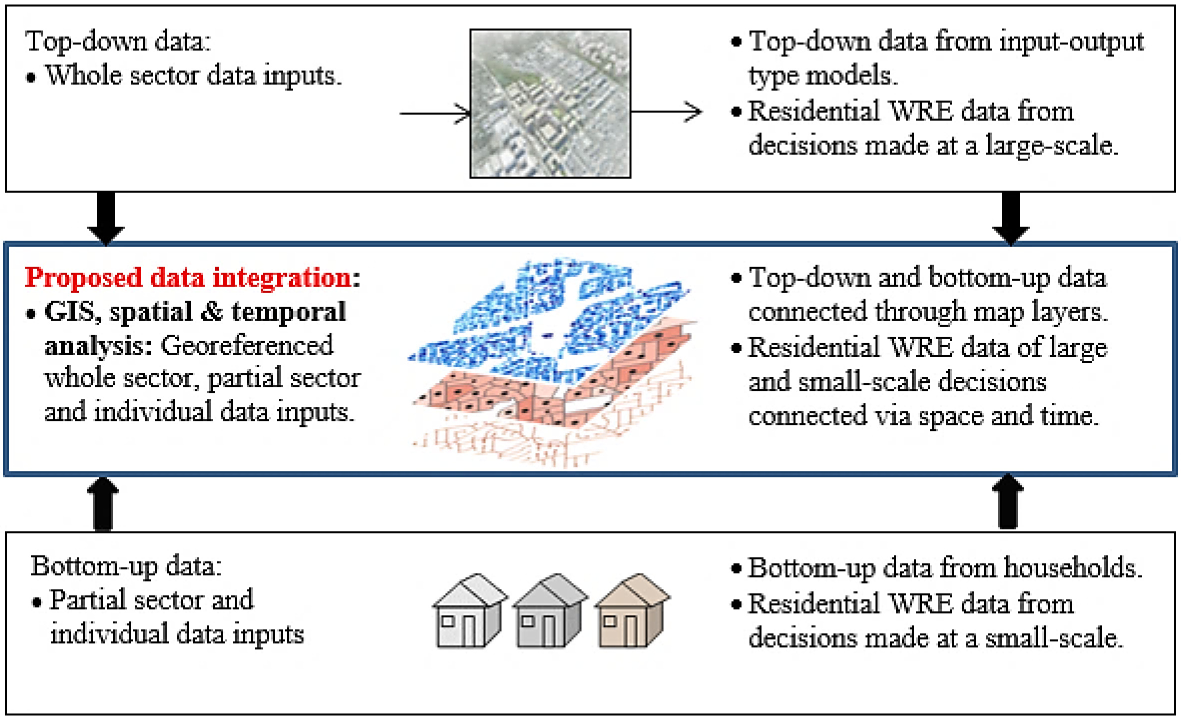

Figure 5-2: Integrating the spatial and temporal scale differences between top-down and bottom-up data in a GIS framework in order to quantify important factors that influence residential WRE use.

The climate impact on residential energy use through environmental influences (e.g. ambient air temperature), are linked to geography (i.e. space) and seasonal changes (i.e. time). The importance of assessing the spatiotemporal impact of environmental influences on household WRE use has been demonstrated through spatiotemporal studies [70]. Example studies include: simulating the urban heat island effect [221, 222], it's impact on household energy use [166], and assessing the trade-offs between residential water and energy consumption in arid climates [223].

Spatiotemporal modelling studies have also been used to identify socio-economic attributes of demographic groups. Investigating the socio-economic attributes of water and energy consumption patterns in GIS would assist in the identification of effective conservation measures related to the conservation practices for a given region. Moreover, spatiotemporal modelling would highlight conservation measures that are effective in one region but may not be as effective in another region [25]. Previous demographic studies using spatiotemporal methods have identified the socio-economic influences on residential water consumption [224, 225], and energy consumption [151, 226, 227], thus, socio-economic influences of end use behaviour contributing to water and energy conservation practices can also be identified.

The importance of modelling the spatiotemporal changes in resource use resulting from upgrades in water appliance technology have also been demonstrated through: energy savings of solar water heaters [141, 228], and the geothermal potential for ground source heat pump systems [229].

5.5.1. Conceptual spatiotemporal WRE model

The proposed conceptual model of quantifying WRE use (Figure 5-3) synthesizes modelling insights gained from research conducted in Chapters 3 and 4 of this study. This model enables multi-scale spatiotemporal investigations of residential water-energy nexus issues.

There were five distinct stages for the proposed conceptual spatiotemporal WRE model quantification of water-energy interactions across scales of decision making through the integration of top-down and bottom-up data. The five stages included:

(i) Spatiotemporal referencing of data inputs and the setup of data layers in the WRE geodatabase (Figure 5-4).
(ii) Grouping analysis in GIS separating water and energy use into four groups (i.e. low, moderate, high, and very high)(Figure 5-5).
(iii) Regional ResWE model specification for environmental, behavioural and technological parameters for each of the four groups (see Chapters 3 and 4) followed by model verification using empirical water and energy data for each group (see Chapter 4).
(iv) Multilevel regression analysis and spatial regression analysis in GIS identifying key factors (e.g. socio-economic factors) on WRE use for each group.
(v) Scenario analysis determining the impacts of demand management programs and area specific rebate programs on regional water use, WRE use, related GHGs (see Chapter 4) and the subsequent implications for localised infrastructure management.

The first stage of the conceptual model is the geodatabase build of significant datasets (Figure 5-4). Shapefiles of important data for different layers of information were developed for modelling and analysis of residential WRE in GIS. For example, ABS census data was used as a source of population data for the project which was accessed through the TableBuilder Pro database: *Counting Persons, Place of Usual Residence* and *2074.0 Census of Population and Housing Mesh Block Counts, 2011*. The TableBuilder Pro database provided the proportions of family composition for ASGS digital boundaries with SA1 level data as the highest resolution available whilst the second dataset provided the number of people and dwellings per Mesh Block [209, 230]. Single age (0-116 years) population counts were generated using SA1 resolution data for SA2 areas. The Mesh Block scale population and dwelling counts corresponding to each SA2 area were identified and accessed through the *2074.0 Census of Population and Housing Mesh Block Counts, 2011* data cube [209]. KMZ files of population data was uploaded and converted into an ArcGIS layer thereby sidestepping the need to geocode the population data. Sources of data that have been collected for the WRE geodatabase development can be found in Chapter 4, Table 4-1.

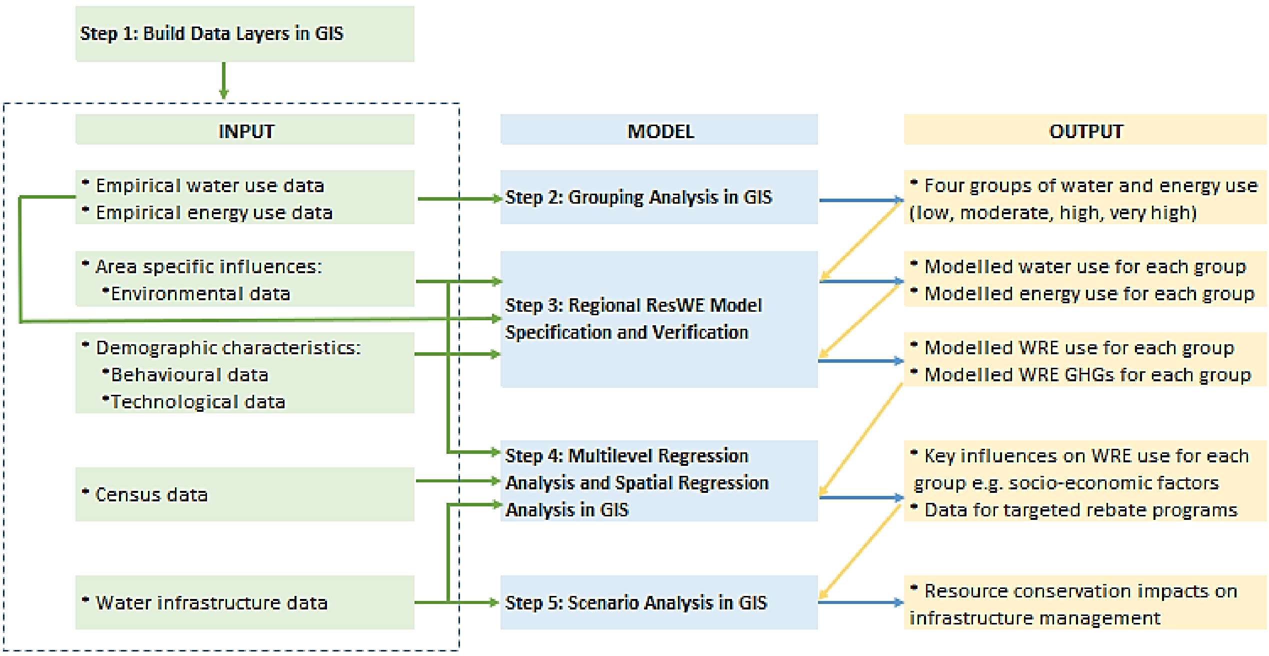

Figure 5-3: Conceptual spatiotemporal model of regional scale residential WRE modelling in GIS.

The second stage of the conceptual spatiotemporal WRE model separated water and energy use rates into four distinct groups (i.e. low, moderate, high, and very high) using the *Grouping Analysis* tool in ArcGIS (Figure 5-5). To capture seasonal extremes, water and energy use rates from summer and winter months were correlated to land use size of SA1 areas. The accompanying grouping analysis report contains a: box and whiskers plot of global statistics, groupwise summary of statistics, variable wise summary of statistics, and a parallel box plot of all four categories of combined water and energy use (i.e. low, moderate, high, and very high) correlated with land size.

The third stage of the conceptual spatiotemporal WRE modelling process is focused on the regional ResWE model. This stage is focused on model specification for key environmental, behavioural and technological parameters for each of the four groups (i.e. four ResWE model inputs) and regional ResWE model verification for each group using empirical water and energy data. This is followed by generating WRE use outputs which are then uploaded into the WRE geodatabase as shapefiles using SA1 level digital boundaries. The regional ResWE modelling process is detailed in Chapter 4.

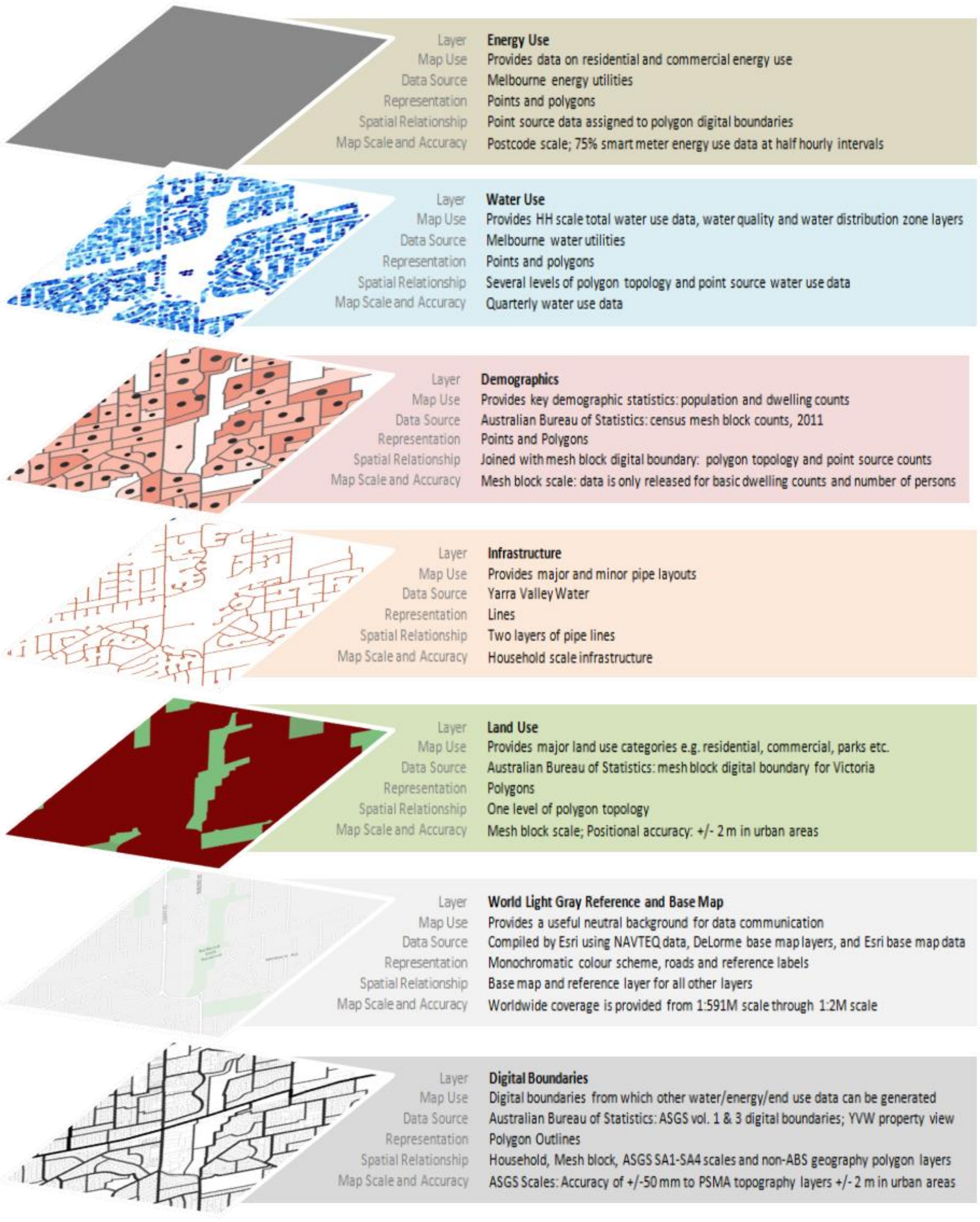

Figure 5-4: Spatially referenced data layers built and stored for spatiotemporal WRE modelling in the WRE geodatabase.

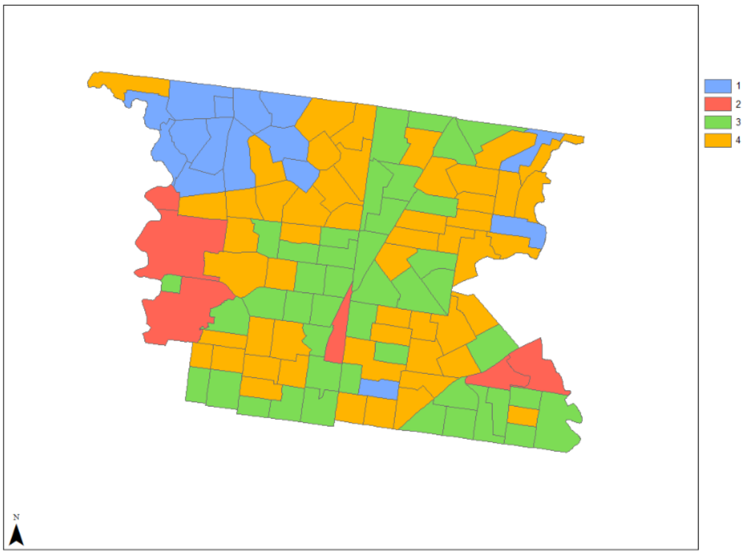

Figure 5-5: Example of an SA1 level grouping analysis of the combined water and gas use for investigating water-energy behaviour patterns of different groups (i.e. low (red), moderate (green), high (orange), and very high (blue)) .

The fourth stage of the conceptual spatiotemporal WRE model is focused on identifying key factors that affect WRE use for each group using multilevel regression analysis and spatial regression analysis in GIS. Multilevel regression analysis is suitable for assessing data inputs from multiple spatial and temporal scales. For example, queries that connect resource consumption to individual level inputs (e.g. end use behaviour such as choice of clothes washing temperature), household level inputs (e.g. water appliance technology such as clothes washer type), regional level inputs (e.g. environmental conditions such as ambient air temperature), and water utility level inputs (e.g. water restrictions). Another example application of multilevel regression analysis would be the investigation into the causes of the CWT impact on WRE use within a water utility delivery zone. This will most likely be correlated to regional characteristics (e.g. source water temperature) more so than household characteristics (e.g. clothes washer type) or individual characteristics (e.g. clothes washing temperature). Multilevel regression analysis will be used to determine factors across different spatial and temporal scales (e.g. utility and end user decisions) that affect WRE use. Additionally, spatial regression analysis using a spatial weights matrix will be used to determine the key socio-economic factors (e.g. education, income etc.) that characterise each of the four groups, thus, correlating socio-economic factors with levels of water and energy use. The key outcome from both of these regression analysis techniques is the fundamental understanding of the key influences in resource use in order to develop resource conservation programs.

The final stage of the conceptual spatiotemporal WRE model is focused on determining the impacts of demand management programs and area specific rebate programs on regional water use, WRE use, and related GHGs through scenario analysis (see Chapter 4). For example, the changes in resource use from each demand management scenario for each group (i.e. low, moderate, high, and very higher resource users) will be mapped onto shapefiles of the major and minor water infrastructure layout. Thus, providing a direct means of determining the change in resource use impacts on supporting infrastructure. The visual mapping of changes in resource use across large scale water and energy infrastructure, provides a powerful tool for determining localised infrastructure management i.e. prioritising infrastructure upgrades. An example of major water pipe attributes uploaded into the WRE geodatabase is presented in Appendix E, Table E-3.

A key feature of the conceptual spatiotemporal WRE model presented here, is the ability to simultaneously evaluate the impact of the variability in the key factors that affect WRE use. In particular, multilevel regression enables the simultaneous assessment of variability in individual characteristics (i.e. end use behaviour), household characteristics (i.e. water appliance technology), regional characteristics (i.e. environmental conditions), and utility level characteristics (i.e. infrastructure & policies). This is a significant development over current WRE modelling methods where simultaneous assessment of heterogeneity across scales is limited. For example, the household scale WRE model presented in in Kenway et al. [94] applied a sensitivity analysis of an averaged CWT input value, over a yearlong time scale, for a specified set of household characteristics. Chapter 3 focused on the regional spatiotemporal change in CWT values and the subsequent WRE use impact on the households characterised in Kenway et al. [94]. Whilst, the regional ResWE model developed in Chapter 4 improved upon the Kenway et al. [94] household scale model by including household heterogeneity of behaviour and technology as well as a temporal change of CWT values. The conceptual spatiotemporal WRE model presented here, couples the models developed in Chapters 3 and 4 to simultaneously asses the spatiotemporal variability of CWT and household heterogeneity impacts of residential WRE use. Spatiotemporal WRE modelling in GIS advances the spatiotemporal assessment of factors that significantly contribute to WRE use.

In summary, spatiotemporal WRE modelling in GIS enables the integration of top-down and bottom-up WRE information, which leads to improved WRE management across the utility and residential sector interface.

5.6. Conclusion

The conceptual spatiotemporal WRE model is proposed for realistic forecasting of regional water-energy interactions in the residential sector. This will provide essential information for improving the resilience of urban water-energy systems. Spatiotemporal modelling of residential WRE is intended to investigate the connections between utility decisions and residential end use decisions. To achieve this, it is necessary to integrate top-down, and bottom-up data connected through space and time. By identifying key influences on residential WRE and spatially distinct patterns of WRE the conceptual model will help tailor resource conservation opportunities. Ultimately, this work will geographically connect WRE consumption to localised infrastructure systems and provide insights to asset management priorities.

In summary, the major contribution of this chapter is the proposed conceptual framework for spatiotemporal WRE modelling in GIS to integrate: (i) utility scale data such as rebate schemes and demand management programs, and (ii) household scale data such as shower use and clothes washing use. Increasing the integration of modelling water-energy interactions across the utility and residential-scale broadens the understanding of water-energy trade-offs and potential solutions that can be used to reduce consumption of resources by utilities and consumers.

Chapter 6. Conclusions, Discussion and Recommendations

The major findings of this PhD research are summarised as conclusions, discussion and recommendations for each research objective (RO) articulated in section 1.2. Application of the research findings to householders as well as water utility and government policies have been discussed. The final section highlights recommendations for future model development.

6.1. Conclusion

This research investigated opportunities to attain a whole-of-system reduction in water-related energy (WRE) consumption across the water utility and residential sector interface. Three different modelling approaches were used. In RO 1, the water utility influence on residential WRE use was investigated through the water infrastructure interaction with environmental conditions which resulted in cold water temperature (CWT) variability. The subsequent implications for hot water system (HWS) energy consumption guidelines was evaluated through modelling the spatiotemporal variability of the CWT supplied to households then quantifying this parameters influence on household WRE use. In RO 2, the residential influence on regional resource consumption was investigated through interactions between household water appliance technology and end use behaviour. The subsequent implications for water utility mandates was evaluated through a regional scale application of the ResWE model quantifying regional water, WRE use and associated GHGs from household scale decisions. Finally, in RO 3, a method for integrating top-down and bottom-up data from different spatial and temporal scales was proposed. The method was developed to increase the information available for quantifying WRE and managing urban water systems across the water utility and residential sector interface. This was done illustratively through a conceptual model that coupled the regional ResWE model to a Geographic Information System (GIS) platform.

6.2. RO 1: Investigate the Water Utility Influence on Residential WRE Use through the Water Supply Temperature

In most WRE studies, environmental parameters such as CWT are often not used to evaluate household WRE use. Alternatively, Australian Standards for HWS energy evaluation apply static modelling conditions where a base CWT value is assumed to have a negligible impact on household WRE. At best, monthly average CWTs are used to represent water supply temperature for large geographical regions when quantifying HWS energy consumption. In Chapter 3, this PhD study evaluated the spatiotemporal variability of CWT within a water utility supply area, on a monthly basis. The demonstrated change in CWT occurred over a small geographical area (4000 km^2) and is significantly different to AU/NZS standardised values.

Chapter 3 of this study also presented a spatial statistical analysis of the CWT variability impact on household WRE use through monthly maps of hot zones (i.e. spatial cluster of warmer than average CWT), cold zones (i.e. spatial cluster of colder than average CWT) and neutral zones (i.e. no spatial correlation of CWT values). Hot zones were located in densely urbanised regions and at best, reduced household WRE use by -17% (-640 kWh/hh.yr). Concurrently, cold zones were mostly located in sparsely urbanised regions and increased household WRE use up to +19% (+680 kWh/hh.yr). These results answered the research question '*How does the variation in cold water temperature impact residential WRE use?* This study presented the first spatiotemporal map of CWT variability across a water distribution network. This work effectively communicated the inherently dynamic nature of CWT. This observation has not previously been emphasized in other studies in this field of research [68, 71, 139] and as a result, the impact of the dynamic nature of CWT and this impact on household WRE use has not previously been captured. A significant contribution of this work is the importance of including CWT variability when quantifying residential WRE use. More importantly however, this work demonstrated how the interaction between infrastructure and the environment affected household WRE consumption.

The novel application of spatial analysis for CWT zoning maps led to the key recommendation that maps of CWT zones be produced and made available for public knowledge. This recommendation will enable individuals to be informed of the energy consumption impact of their hot water usage behaviour in line with CWT zone maps.'

Additionally, it is recommended that water utilities should consider CWT management as a novel opportunity to reduce WRE for utilities and residents. This research estimated that the CWT variability impact on household WRE was up to three times the amount of energy required by Melbourne water utilities to provide water supply and sewage disposal services. However, CWT management is currently not a primary water management practice. Current practice leads to residents bearing the impact of CWT variability on household WRE use, not the utility. Therefore, the water utility level recommendation is to include an investigation into best practices for upgrading water infrastructure to reduce CWT variability impact on household WRE use, thus, reduce WRE use across the utility and residential sector interface. For example, more active management of CWT as part of the utility's service (e.g. use of heat exchangers to deliver hotter or colder water), and an active selection of water for delivery based on its temperature in winter or summer (e.g. from different layers within water storage). Ultimately, active management of CWT could be proposed as a potential carbon offset scheme for water utilities. In particular, this research proposes this outcome be achieved through the use of State government renewable energy targets as an incentive for water utilities to include CWT management for reducing regional scale residential WRE demand.

Evaluation of CWT variability impact on household WRE consumption also demonstrated that Australian Standards should reconsider the assumption that CWT is a constant value or an averaged value that covers a large geographical region. In particular, Australian Standards relating to energy labelling of HWSs and the allocation of renewable energy certificates. This PhD study found that CWT variability (-21 to +47% of the prescribed value) did not have a negligible impact on off-peak energy use, thus, electric HWSs operating on off-peak energisation schemes most likely will not deliver the expected performance conditions under the specified energy label. Of particular importance, was the lack of agreement between the mean CWTs for the study site and the AS/NZS 4234 prescribed CWTs for the same site. Research findings conclude that there is an inherent prediction error for estimates of residential WRE demand and associated GHG emission savings when assessing HWS performance and issuing renewable energy certificates. Given the results of this PhD study, the policy level recommendation is the investigation into updating CWT values for Australian Standards associated with HWS energy consumption evaluation (e.g. AS/NZS 4234:2008 and AS/NZS 1056.4:1997).

In conclusion, CWT variability is significant and affects household WRE use. Thus, measuring and mapping CWT variability is important for reducing WRE use across the utility and residential sector interface, and updating AS/NZS standards.

6.3. RO 2: Develop a Method to Quantify the Residential Influence on Regional WRE Use

Most studies quantifying residential WRE are presently limited by relying on detailed data from a small number of households to represent a whole region, or they rely on highly aggregated data to extract household averages for policies. To address this limitation in Chapter 4, this PhD adapted a detailed household scale WRE model for a regional scale application. This was done by characterising end use variability between individual households through census data and local water authority information for quantifying WRE use through the regional ResWE model.

The regional ResWE model developed in Chapter 4 captured end use variability through the four biggest determinants of WRE consumption: household composition, HWS type, shower use, and clothes washer use whilst the CWT variability (key recommendation from Chapter 3) was incorporated by using the mean CWT for each month of analysis. Chapter 4 demonstrated that out of the four biggest determinants of WRE consumption, shower use systems offered the most substantial lever for reducing resource use. This outcome is comparable to other studies in this field [48, 98, 105]. However, in this study, it is emphasized that both technology and behaviour change is required for: an estimated annual water reduction of 27% (0.8 GL/yr), WRE-electricity reduction of 15% (2.3 GWh/yr), WRE-gas reduction of 48% (23.9 GWh/yr), and WRE-GHG reduction of 28% (7.8 ktCO_2-e/yr). These results answered the research question *'How does household scale technology and behaviour affect regional water, WRE use and associated emissions?'* Another contribution of this work was the identification of significant recommendations for households and utilities in order to improve management of WRE. This contribution was derived from evaluating water-energy interactions within households and across a region.

For household scale technology, the increased adoption of water efficient showerheads is recommended but a careful consideration of water efficient clothes washers in line with clothes washing temperature preferences is recommended i.e. warm wash households can adopt water efficient clothes washers but cold wash households would increase their WRE use in doing so. A key outcome of this research is that end use behaviour had a greater impact on household WRE consumption than changes in household end use technology. For example, changes in shower use behaviour reduced WRE by 50-90% whilst changing shower use technology reduced WRE by 20-65% in low energy households. Consequently, householders can achieve significant water and energy savings through changing their own shower use behaviour without investing in shower use technology. Analysis of clothes washing use led to the same conclusion. Thus, the individual level recommendation is the increased awareness that choices in end use behaviour have the greatest impact on resource use. This means that all individuals, regardless of demographics or the ability to upgrade to water efficient appliances, would be able to substantially reduce their WRE footprint by taking shorter showers and where possible, reducing hot water usage by switching to cold wash clothes washing.

For regional scale recommendations, this research demonstrated the need to understand the interactions between household end use technology and behaviour for region-specific policy formation. This is particularly important for clothes washing. Current water utility mandates prescribe householders to switch to a water efficient clothes washer as a means of saving water within households and reducing regional water demand during times of water scarcity. Another significant water utility mandate is to reduce GHG emissions of utilities. Chapter 4 demonstrated that an increase in the penetration of water efficient clothes washers reduced water demand for households and utilities but increased the WRE burden to householders, thus, increasing regional GHG emissions. Consequently, there is a conflictive outcome between water utility mandates. The policy level recommendation is the investigation into combined policies for simultaneously achieving water efficient, WRE efficient and GHG reduction mandates. A potential further analysis would be to include the costs of the actions to analyse the cost effectiveness of each action. Additional information on combined water and energy efficiencies of applicable household appliances is also recommended i.e. combined water and energy labelling of appliances. Given the results of this PhD, it is suggested that the interaction between technology and behaviour at regional scales is considered a priority for water appliance technology based rebate schemes.

A significant outcome of this study was the impact of household composition on regional resources. Small occupancy households were the highest consumers per capita where 53% of the population lived in 73% of the household stock and consumed 59% of resources. In contrast, large occupancy households were the lowest consumers per capita, lived in a smaller proportion of the household stock and consumed far less resources than small occupancy households. These findings are an important contribution to the literature on residential WRE as current predictive models on resource use do not include demographic consumption patterns. Additionally, projected population trends indicated that small occupancy households were on the rise. Thus, this work suggests that further research is needed in the water-energy nexus of small occupancy households. The utility or government level recommendation is the inclusion of resource use for different demographic groups in predictive resource use models.

In conclusion, a predictive model was developed for investigating factors influencing household WRE use and identify levers that simultaneously reduced regional water use, WRE consumption and GHG emissions. It was discovered that accounting for demographic consumption patterns is important for future predictive models on resource use. This research demonstrated how interactions between technology and behaviour at household and regional scales ultimately determined water, WRE consumption and associated GHGs for a specific region. Consequently, given the results of this PhD it is strongly recommended these interactions be considered when forming policies aimed at reducing either water or energy or GHGs at the regional scale.

6.4. RO 3: Propose how to Integrate Information from Water and Residential Sectors to Reduce WRE

Modelling WRE is important for determining how to reduce urban resource use. WRE use depends on decisions made by utility's (top-down data) and end users (bottom-up data). Utility decisions generally affect larger spatial scales and longer time spans than end user decisions. Thus, WRE modelling needs to encompass multiple spatial and temporal (spatiotemporal) scales to effectively capture decisions made by utility's and end users. However, most WRE models do not have the capacity to model changes in WRE decisions across multiple scales. Chapter 5 proposes spatiotemporal modelling of WRE data from the regional ResWE model in a Geographic Information System (GIS) platform in order to store and statistically process layers of data (e.g. water and WRE data), for a specified geography and time.

Chapter 5 of this PhD proposed a conceptual framework for coupling the regional ResWE model (developed in Chapter 4) to a GIS platform for spatiotemporal WRE modelling. This enabled modelling of residential water-energy interactions between infrastructure, environment, technology, and behaviour. For example, spatiotemporal WRE modelling in GIS provided the ability model utility decisions on households (e.g. CWT variability and infrastructure data from Chapter 3), and model household decisions on regional resources (e.g. household technology and behaviour data from Chapter 4). This capacity of spatiotemporal WRE modelling in GIS i.e. the ability to store and analyse layers of water and WRE data that span different spatial and temporal scales, provides the framework required to integrate top-down and bottom-up WRE data. Thus, integrating utility scale data, with household scale data, to analyse WRE decisions made over differing spatial and temporal scales. Coupling the ResWE model to a GIS platform answered the research question *'How can information be integrated across the spatial and temporal scales needed to reduce WRE use across residential and water sectors?'* Current studies have started to use spatiotemporal modelling for quantifying utility water and WRE reductions from demand management programs [135, 231] but have not as yet quantified reductions in water and WRE from the residential sector. Thus, a key contribution of this work is the novel approach to integrating the spatiotemporal scales of WRE data required to effectively model and ultimately reduce WRE use across the interface between water utility and residential sectors.

A major advantage of integrating top-down WRE data with bottom-up WRE data in a GIS platform is the foundation to develop area-based resource conservation programs. Resource conservation opportunities include: the introduction of area-based rebate schemes, tailored upgrades in water appliance technologies and increased support for water and energy conservation practices through tailored education programs promoting changes in end use behaviour. Changes in end use behaviour is particularly important, as it has a far greater impact on reducing WRE use than upgrades in water appliance technology. Thus, a greater understanding of the motivation behind water and energy conservation practices is needed. This can be achieved through an improved understanding of the key influences of WRE use through multilevel regression analysis which is suitable for assessing data inputs from multiple spatial and temporal scales. For example, multilevel regression analysis enables queries that connect resource consumption to individual level inputs (e.g. end use behaviour such as clothes washing temperature), household level inputs (e.g. water appliance technology such as clothes washer type), regional level inputs (e.g. environmental conditions such as changes in ambient air temperature), and water utility level inputs (e.g. water restrictions during times of drought). Additionally, spatial regression analysis can be used to determine the key socio-economic factors (e.g. education, income etc.) that describe predefined groups of low, moderate, high and very high WRE use, thus, correlating socio-economic factors with levels of water and energy use. Ultimately, multilevel regression analysis identifying key factors that affect WRE use (e.g. utility and end user decisions) and spatial regression analysis identifying key socio-economic factors associated with levels of resource use, both provide the information required for the development of targeted rebate programs that address residential water-energy nexus issues.

The key recommendation of this objective is the proposed integration of top-down and bottom-up WRE data across utility and residential scales. Spatial and temporal alignment of key WRE datasets (water, energy, census) is key for further research into water-energy nexus issues. This will be done through applying the conceptual model proposed in Chapter 5, in the next phase of research to identify the key socio-economic factors that influence levels of WRE use. Additionally, for future work and ease of analysis, it is recommended that an investigation be carried into how to establish a spatially referenced water and energy data collection system from utilities for continued research in residential water-energy nexus issues.

In conclusion, it is proposed that the regional ResWE model developed coupled to a spatiotemporal framework such as GIS provides the structure to integrate top-down (utility) data with bottom-up (household) data. Multilevel regression analysis can be applied for identifying and understanding key levers for reducing resource use. Ultimately, the coupled WRE model will broaden the understanding of water-energy trade-offs and potential solutions that can be used to reduce the consumption of water, WRE and associated emissions by utilities and end users.

6.5. Future Model Recommendations

Assumptions and simplifications used in the regional ResWE model, were made in order to contain the scope of this work. Future work on the assumptions and simplifications used in the regional ResWE model would reduce the uncertainty in the findings presented in this thesis (i.e. the potential to overestimate or underestimate WRE consumption):

- Average monthly CWT values were derived from measurements within the study site (i.e. postcode) boundary. Future models could derive the average monthly CWT values by utilising the water utilities' water quality zones as the boundary of analysis due to the relationship between water quality and CWT [142, 170]. This would improve WRE use estimates for all end uses that rely on water heating.
- Household composition was restricted to 4 key groups: family with children, family without children, single and group households. Single households (with and without children) were absorbed into family households. Future models could expand the number of household composition types to include single households (with and without children) as two separate categories. Thus, improving WRE estimates for demographic groups.
- Medium sized HWSs were used as a modelling simplification for all household composition types i.e. family households (with and without children), single households and group households. Future models could improve WRE estimates for HWSs and demographic groups by allocating small, medium and large sized HWSs corresponding to the relevant household size.
- Shower water temperature was assumed to be the same temperature preference for both genders however, this is not always the case [98]. Future models could improve WRE estimates for shower use by sourcing separate temperature preferences for males and females.
- The average flowrate for low shower duration was evaluated as the 4-minute shower scenario. Future models could derive the average flowrate for low shower duration as one standard deviation below the average mean shower duration in the base model (i.e. 2.7 min summer, 2.2 min winter, for the study site [199]), thus improving WRE estimates for shower use.
- Hot wash cycles and varied-wash cycles (1% and 19% of the study site households, respectively [183]), were absorbed in the evaluation for a warm wash cycle. Hot wash cycles would yield larger total WRE use results than warm wash cycles whilst varied-wash cycles (i.e. cold, warm or hot wash) could yield smaller or larger WRE results than warm wash cycles alone. Future models evaluating clothes washing use could improve WRE estimates by accounting for hot wash cycles and varied wash-cycles.

- The ambient air temperature dataset included 3 hourly temperature measurements. These readings were averaged daily then aggregated to monthly temperature values in alignment with the temporal scope of the project. Future models could utilise ambient air temperature observations during peak water end use activity time i.e. observations before 9am and/or after 4pm for improved WRE estimates.
- Tap use temperature could improve WRE estimates by sourcing preferred temperatures for tap use activities (e.g. hand washing, teeth brushing, shaving).
- The current study assumed all households participated in an equal amount of outdoor water use for model simplification. Water use estimates could be improved by incorporating a variation in outdoor water use estimates for different dwelling types e.g. little to no outdoor water use for apartment blocks.
- To overcome modelling extreme scenarios, future work would include a Monte Carlo approach to modelling household heterogeneity in the regional ResWE model and a more conservative approach to scenario testing
- It is also recommended that a sensitivity analysis in the regional ResWE model be conducted in order to identify mechanistic components of appliances that have the greatest impact WRE use.

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Appendix A: Chapter 2 Support Information

This appendix presents the support information for Chapter 2 which provides the literature review identifying research gaps and research questions of this thesis. Section A.1 outlines the scope of the preliminary residential water-energy nexus literature review and the method used to summarise the residential WRE literature gap.

A.1. Preliminary Water-Energy Nexus Literature Review

A summary of research gaps for residential water-energy nexus literature including a list of papers by author-date is presented in Chapter 2, Table 2-1 whilst the detailed categorisation of the reviewed literature is presented in Table A-1.

The scope of the preliminary literature review focused on understanding and identifying research gaps in the residential water-energy nexus. The major research gap identified was the need to investigate opportunities to reduce residential WRE consumption within the context of supporting infrastructure systems. Reducing residential WRE consumption was important as it represented the highest proportion of WRE in the urban water cycle. Quantitative, qualitative and review papers on water, WRE and energy use of water supply systems and residential water end use were reviewed.

Three categories were used to summarise the residential WRE literature gap of the water-energy nexus: sector, scale and method (see Chapter 2, Table 2-1).

Sector: Papers from both residential end use and utility sector perspectives were reviewed. The major observation of reviewing studies from the residential and utility sectors was that residential WRE was determined by decisions made at the household scale through residential water end use decisions and at the water utility scale through water infrastructure decisions and demand management programs.

Scale: Both large scale and small scale studies on residential water, WRE and energy use were reviewed. It was noted that most of the large scale residential WRE use studies (city or larger than city scale results) provided information on resource use that could not be correlated with locations, changes in water appliance technology or end use behaviour. Concurrently, most of the small scale residential WRE studies (building scale results) provided detailed information on household water and energy interactions such as changes in water appliance technology or end use behaviour, but these papers weren’t often at a relevant scale of analysis for government or utilities to formulate policies. A need to integrate the information available from utility and residential perspectives was identified as a means of integrating the management of water infrastructure and residential WRE use.

Method: A review of methods determined that resolving the information available between large scale (top-down modelling) and small scale (bottom-up modelling) studies could be addressed with a method of analysis that contained a spatial and temporal component. Thus, studies with a spatiotemporal component that quantified residential WRE were reviewed. However, few spatiotemporal studies on WRE were available. The majority of spatiotemporal studies were on either water or energy management which were not the main focus of this research, thus, were not included in the preliminary summary of literature reviewed (i.e. the spatiotemporal section of water and energy studies would normally have a far greater number, Chapter 2, Table 2-1).

Table A-1: Categorisation of the literature reviewed at the preliminary stages of research

#	Date	Theme	U	R	Method	Quant.	Qual.	Scale
1	Rathnayaka et al. (2015) - Seasonal Demand Dynamics of Residential Water End-Uses	W	N	*	BU: End use data (smart meters), ANOVA; Multiple regression analysis	*	N	I, B
2	Agudelo-Vera et al. (2014) - Water and energy nexus at the building level	W, WRE, E	N	*	BU: SIMDEUM for simulating hot water demand	*	N	B
3	Bartos & Chester (2014) - The Conservation Nexus: Valuing Interdependent Water and Energy Savings in Arizona	W, E, WRE, ERW	*	*	BU: data at individual infrastructure components; scenario; uncertainty; map	*	N	C
4	Elías-Maxil et al. (2014) - Energy in the urban water cycle: Actions to reduce the total expenditure of fossil fuels with emphasis on heat reclamation from urban water	WRE, E	*	*	Review	*	N	C, N
5	Howells & Rogner (2014) - Water-energy nexus: Assessing integrated systems	W, E, WRE, ERW	N	N	Review	N	*	SY
6	Kenway et al. (2014) - Water and energy futures for Melbourne: implications of land use, water use, and water supply strategy	W, WRE	*	*	TD: ABS data; Analytic framework; scenarios	*	N	C
7	Martinez-Expineira et al. (2014) - Households' pro-environmental habits and investments in water and energy consumption: Determinants and relationships	W, E	N	*	Multivariate probit model; Scenario analysis	*	*	B
8	Nair et al. (2014) - Water-energy-greenhouse gas nexus of urban water systems: Review of concepts, state-of-art and methods	WRE, GHG	*	*	Review	*	N	B, C, N
9	Rathnayaka et al. (2014) - Factors affecting the variability of household water use in Melbourne	W	N	*	BU: End use data (smart meters), OLS; Multiple regression analysis	*	N	B
10	Stokes et al. (2014) - Save Water to Save Carbon and Money: Developing Abatement Costs for Expanded Greenhouse Gas Reduction Portfolios	W, WRE, GHG	*	N	BU: Technology based method - EAC Curves;	*	N	F
11	US DOE (2014) - The Water-Energy Nexus: Challenges and Opportunities, Overview and Summary	W, E, ERW, WRE	N	*	Overview	N	*	N
12	Vieira et al. (2014) - Residential water heaters in Brisbane, Australia: Thinking beyond technology selection to enhance energy efficiency and level of service	WRE	N	*	BU: End use (smart meter data); Software: EnergyPlus 8.1	*	N	B
13	Binks et al. (2013) - Detailed Characterisation of Water-Related Energy Use in Households, in Ozwater 2014	W, E, WRE, GHG	N	*	BU: End use (smart meter data); Surveys; Interviews; Sensitivity	*	N	MB
14	Brown et al. (2013) - Actors working the institutions in sustainability transitions: The case of Melbourne's stormwater management	W	*	N	Case study; Interviews; Review; Models of multi-level perspectives	N	*	C
15	Chowdary et al. (2013) - Multi-Criteria Decision Making Approach for Watershed Prioritization Using Analytic Hierarchy Process Technique and GIS	W	*	N	Multi-criteria decision approach - Analytic hierarchy process (AHP) based SYI model (AHPSYI), GIS	*	*	CA
16	Chrysoulakis et al. (2013) - Sustainable urban metabolism as a link between bio-physical sciences and urban planning: The BRIDGE project.	W, E, GHG	*	N	BRIDGE DSS tool; GIS; MCA; Urban water balance; Urban energy balance; Scenario analysis; Optimisation	*	*	C

#	Date	Theme	U	R	Method	Quant.	Qual.	Scale
17	Ferguson et al. (2013) - Diagnosing transformative change in urban water systems: Theories and frameworks	W	*	N	Review of theoretical frameworks; Diagnostic questions;	N	*	C
18	Ferguson et al. (2013) - The enabling institutional context for integrated water management: Lessons from Melbourne	W	*	*	Case study; Workshop; Interviews; TD: Water use data	N	*	C
19	Grant et al. (2013) - Adapting Urban Water Systems to a Changing Climate: Lessons from the Millennium Drought in Southeast Australia	W	*	*	TD: Water budget data	*	*	C
20	Inamdar et al. (2013) - A GIS based screening tool for locating and ranking of suitable stormwater harvesting sites in urban areas	W	*	N	GIS + Sustainability criteria; Urban water balance	*	*	CA
21	Kenway et al. (2013) - Water-related energy in households: A model designed to understand the current state and simulate possible measures	W, E, WRE, GHG	N	*	BU: End use (meter reading); Surveys; Interviews; MFA	*	N	B
22	Laves et al. (2013) - The research-policy nexus in climate change adaptation: experience from the urban water sector in South East Queensland, Australia	W, WRE	*	*	Review	*	*	R
23	Lubega & Farid (2013) - A Meta-System Architecture for the Energy-Water Nexus	W, E	*	N	Brief review; Meta-System Architecture using modelling language: SysML	N	N	SY
24	Makki et al. (2013) - Revealing the determinants of shower water end use consumption: Enabling better targeted urban water conservation strategies	W	N	*	BU: End use data (smart meters), ANOVA; Multiple regression analysis	*	N	MB
25	Miller et al. (2013) - Contribution of Water and Wastewater Infrastructures to Urban Energy Metabolism and Greenhouse Gas Emissions in Cities in India	W, E, WRE, GHG	*	N	TD: Mathematical modelling; city as a box modelling	*	N	C
26	Nasiri et al. (2013) - A system dynamics approach for urban water reuse planning: a case study from the Great Lakes region	W	*	N	TD: Systems dynamics; Causal loop diagrams; Mathematical modelling;	*	N	SY
27	Nguyen et al. (2013) - Development of an intelligent model to categorise residential water end use events	W	N	*	BU: End use data (smart meters); Hidden Markov Model	*	N	MB
28	Novotny (2013), Water-energy nexus: retrofitting urban areas to achieve zero pollution	W, E, WRE, GHG	*	*	BU: Methods outlined in Novotny 2010	*	N	B, D, R
29	Siddiqi & de Weck (2013) - Quantifying End-Use Energy Intensity of the Urban Water Cycle	W, WRE	N	*	BU: MATLAB: MFA, water use in buildings to represent city area	*	N	I, B-C
30	Siddiqi et al. (2013) - Bridging decision networks for integrated water and energy planning	W, E, WRE, ERW	*	*	Stakeholder Analysis	*	*	N
31	Stephan et al. (2013) - Multi-scale life cycle energy analysis of a low-density suburban neighbourhood in Melbourne, Australia	E, GHG	N	*	BU/TD: LCEA software; Uncertainty quantification using interval analysis	*	N	B-D
32	Stokes et al. (2013) - Water Loss Control Using Pressure Management: Life-cycle Energy and Air Emission Effects	W, E	*	N	BU/TD: LCEA	*	N	F
33	Willis et al. (2013) - End use water consumption in households: impact of socio-demographic factors and efficient devices	W	N	*	BU: End use data (smart meters); Stock survey; Questionnaire	*	N	R
34	Zhou et al. (2013) - Drops of Energy: Conserving Urban Water to Reduce Greenhouse Gas Emissions	W, WRE	*	*	TD: I-O analysis of urban water system stages	*	N	C
35	Beal et al. (2012) - Evaluating the energy and carbon reductions resulting from resource-efficient household stock	W, WRE, GHG	N	*	BU: End use (smart meter data); stock information & usage patterns	*	N	I

#	Date	Theme	U	R	Method	Quant.	Qual.	Scale
36	Camci et al (2012) - Rethinking Future of Utilities: Supplying All Services through One Sustainable Utility Infrastructure	W, E	N	N	Overview	N	*	SY
37	Carragher et al. (2012) - Quantifying the influence of residential water appliance efficiency on average day diurnal demand patterns at an end use level: A precursor to optimised water service infrastructure planning	W	N	*	BU: End use data (smart meters); Statistical analysis	*	N	B
38	Ferrari et al. (2012) - Learning from interventions aimed at mainstreaming solar hot water in the Australian market	E, WRE, GHG	N	*	Review; TD: End use data (stock appliance numbers)	*	*	ST, N
39	Howard et al. (2012) - Spatial distribution of urban building energy consumption by end use	E, WRE	N	*	EUEI; Multiple linear regression; GIS	*	N	B-C
40	Hussey & Pittock (2012) - The Energy-Water Nexus: Managing the Links between Energy and Water for a Sustainable Future	W, E, ERW	N	N	Review; Case studies	N	*	SY
41	Ilha & Ribeiro (2012) - Adoption of technology by the low-income population segment: The low-cost hot water heater case	W, WRE	N	*	Case Study; Education workshops; Interviews;	N	*	B
42	Lee & Tansel (2012) - Life cycle based analysis of demands and emissions for residential water-using appliances	W, WRE, GHG	*	*	TD/BU: LCA of appliances; EIO-LCA tool	*	N	B
43	Panagopoulos et al. (2012) - Mapping Urban Water Demands Using Multi-Criteria Analysis and GIS	W	N	*	Multi-criteria spatial data analysis; Analytical hierarchy process;	*	*	C
44	Plappally et al. (2012) - Energy requirements for water production, treatment, end use, reclamation, and disposal	W, WRE	*	*	Review	*	N	B, C, N
45	Sanders & Webber (2012) - Evaluating the energy consumed for water use in the United States	W, E, WRE	*	*	TD: Sectoral assessments of energy use & BU: energy-for-water on a component-wise & service	*	N	N
46	Stephan et al. (2012) - Towards a comprehensive life cycle energy analysis framework for residential buildings	E, GHG	N	N	TD/BU: LCEA software	*	N	B
47	Strengers & Maller (2012) - Materialising energy and water resources in everyday practices: Insights for securing supply systems	W, E, GHG	N	*	Interviews; Theories of social practice;	N	*	B
48	Beal et al. (2011) - SEQ residential end use study	W	N	*	BU: End use data (smart meters)	*	N	R
49	Brazeau & Edwards (2011) - A Review of the Sustainability of Residential Hot Water Infrastructure: Public Health, Environmental Impacts, and Consumer Drivers	WRE	N	*	Review	N	*	SY
50	Dominguez et al. (2011) - Tackling uncertainties in infrastructure sectors through strategic planning: the contribution of discursive approaches in the urban water sector	W	*	N	Case study	N	*	N
51	Fuller & Crawford (2011) - Impact of past and future residential housing development patterns on energy demand and related emissions	E, WRE, GHG	N	*	TD: DEWHA data (BU: End use modelling 1990-2020, back calculated to 1950);	*	N	B-C
52	Goto et al. (2011) - Consumer choice on ecologically efficient water heaters: Marketing strategy and policy implications in Japan	E, WRE, GHG	N	*	BU: Survey; Mixed logit and nested logit models; hypothesis testing	*	N	B-R-N

#	Date	Theme	U	R	Method	Quant.	Qual.	Scale
53	Hering et al. (2011) - Moving Targets, Long-Lived Infrastructure, and Increasing Needs for Integration and Adaptation in Water Management: An Illustration from Switzerland	W	*	N	Case study	N	*	N
54	Kenway et al. (2011) - Quantifying water-energy links and related carbon emissions in cities	W, WRE, GHG	*	*	TD: literature and data review of sector averages; Mathematical modelling	*	N	C
55	Kenway et al. (2011) - The connection between water and energy in cities: a review	W, E, WRE	*	N	Review	N	*	C
56	Lee et al. (2011) - Influence of residential water use efficiency measures on household water demand: A four year longitudinal study	W	N	*	BU: End use data (water bills); statistical analysis	*	N	MB
57	McMahon & Price (2011) - Water and Energy Interactions	W, E, WRE, ERW	*	*	Review	*	N	ST, N
58	Minne et al. (2011) - Water, Energy, Land Use, Transportation and Socioeconomic Nexus: A Blue Print for More Sustainable Urban Systems	W, E, ERW, WRE	*	*	Overview; Case study; GIS	*	N	C
59	Muthukumaran et al. (2011) - Quantification of potable water savings by residential water conservation and reuse - A case study	W	N	*	BU: End use data (meter read); Interviews, Surveys	*	*	B
60	Perrone et al. (2011) - Gaining Perspective on the Water-Energy Nexus at the Community Scale	WRE, ERW	*	*	TD/BU: Facility scale data: WEN Tool; Sensitivity and scenario testing	*	N	F
61	Proenca et al. (2011) - Potential for electricity savings by reducing potable water consumption in a city scale	W, WRE	N	*	TD: averaged data inputs per sector; BU: end use per building data; Mathematical modelling	*	N	C
62	Rothausen & Conway (2011) - Greenhouse-gas emissions from energy use in the water sector	W, WRE, GHG	*	*	Review	*	N	SY
63	Scott (2011) - The water-energy climate nexus: Resources and policy outlook for aquifers in Mexico	W, WRE, E, GHG	*	N	TD: Mathematical material flow analysis; variations of IPCC scenario analysis	*	N	N
64	Scott et al. (2011) - Policy and institutional dimensions of the water-energy nexus	W, E, ERW	N	N	Review	N	*	R
65	Siddiqi & Anadon (2011) - The water-energy nexus in Middle East and North Africa	W, E, WRE, ERW	*	N	TD: Systematic quantitative evaluation	*	N	N
66	Stamminger (2011) - Modelling resource consumption for laundry and dish treatment in individual households for various consumer segments	W, WRE	N	*	BU: End use data; Mathematical modelling	*	N	B
67	Willis et al. (2011) - Alarming visual display monitors affecting shower end use water and energy conservation in Australian residential households	W, WRE, E	N	*	BU: End use data (smart meters)	*	N	B-C
68	Boyle et al. (2010) - Delivering Sustainable Infrastructure that Supports the Urban Built Environment	W, E	N	N	Workshop	N	*	SY
69	Conrad et al. (2010) - Key Decisions for Sustainable Utility Energy Management	W, WRE, E	*	*	Review; Workshop	N	*	SY
70	Fidar et al. (2010) - Environmental implications of water efficient microcomponents in residential buildings	W, WRE, GHG	N	*	BU: End use data from technical guide; Mathematical modelling; Scenario	*	N	B

#	Date	Theme	U	R	Method	Quant.	Qual.	Scale
71	Pakula and Stamminger (2010) - Electricity and water consumption for laundry washing by washing machine worldwide	W, E, WRE	N	*	BU: End use data; Mathematical modelling	*	N	B
72	PMSEIC (2010) - Challenges at Energy-Water-Carbon Intersections, Impact Statement	W, E, WRE, ERW, GHG	*	*	Overview	N	N	SY
73	Shimoda et al. (2010) - City-level energy and CO2 reduction effect by introducing new residential water heaters	W, E, WRE, GHG	N	*	BU: Simulation model developed by authors	*	N	B-C
74	Wong et al. (2010) - Shower water heat recovery in high-rise residential buildings of Hong Kong	WRE	N	*	BU: End use data (survey); Mathematical modelling; Scenario	*	N	B
75	Flower (2009) - An Integrated Approach to Modelling Urban Water Systems	W, E, WRE, GHG	*	*	BU: Mathematical modelling (Operational LCA); Scenario	*	N	B-C
76	Jorgensen et al. (2009) - Household water use behaviour: An integrated model	W	N	*	Review; Integrated social & economic model	N	*	B
77	Leidl & Lubitz (2009) - Comparing domestic water heating technologies	E, WRE	N	*	Case study; Economic analysis; TD: housing stock data	*	N	C
78	Retamal & Turner (2009) - Unpacking the energy implications of distributed water infrastructure: how are rainwater systems performing	W, WRE	*	N	Review; hh scale measurements of rainwater tank energy use	*	N	B-C
79	Stokes & Horvath (2009) - Energy and Air Emission Effects of Water Supply	W, E, WRE, GHG	*	N	TD/BU: Hybrid LCA; DSS: WEST tool	*	N	ST
80	Swan & Ugursal (2009) - Modeling of end-use energy consumption in the residential sector: A review of modeling techniques	E	N	*	Review	N	*	SY
81	Goldstein et al. (2008) - The Energy-Water Nexus and information exchange: challenges and opportunities	W, E	N	N	Case study	N	*	C, R, ST
82	Burch & Christensen (2007) - Towards Development of an Algorithm for Mains Water Temperature	W	*	N	BU: End Use Data water & air T	*	N	C
83	Hajkowicz & Collins (2007) - A Review of Multiple Criteria Analysis for Water Resource Planning and Management	W	N	N	Review	N	*	SY
84	Kennedy et al (2007) - The Changing Metabolism of Cities	W, E, GHG	*	N	Review	*	*	C
85	VandeWeghe & Kennedy (2007) - A Spatial Analysis of Residential Greenhouse Gas Emissions in the Toronto Census Metropolitan Area	E, GHG	N	*	LCA: Input-Output for each census tract; GIS for mapping	*	N	C
86	Arpke & Hutzler (2006) - Domestic Water Use in the United States, A Life-Cycle Approach	W, WRE	*	*	TD: Operational LCA, national energy data stats; BEES v3.0 for impact assessment	*	N	N
87	Saliba & Gan (2006) - Energy Density Maps in Water Demand Management	WRE	*	N	BU: facility scale data; Mathematical modelling; GIS for mapping	*	N	F
88	Engel-Yan et al. (2005) - Toward sustainable neighbourhoods: the need to consider infrastructure interactions	W, E	N	N	Review	N	*	B-D
89	Sahely et al. (2005) - Developing sustainability criteria for urban infrastructure systems	W, GHG	*	N	Case study; Sustainable infrastructure framework	*	*	C
90	Crawford & Treloar (2004) - Net energy analysis of solar and conventional domestic hot water systems in Melbourne, Australia	E, GHG	N	*	LCA of hot water systems; Hybrid process analysis (BU) and input-output analysis (TD)	*	N	B

#	Date	Theme	U	R	Method	Quant.	Qual.	Scale
91	Lundie et al (2004) - Life Cycle Assessment for Sustainable Metropolitan Water Systems Planning	W, E, WRE	*	*	BU: Facility scale data inputs; LCA model that integrates water & wastewater	*	N	C
92	Turner et al. (2004) - Results of the Largest Residential Demand Management Program in Australia	W	N	*	BU: End use data (meter read)	*	N	B, C
93	Arbues et al. (2003) - Estimation of residential water demand: A state-of-the-art review	W	N	*	Review	N	*	SY
94	Cheng (2002) - Study of the inter-relationship between water use and energy conservation for a building	W, E, WRE	*	*	BU: End use data; Direct measurements of HWSs; Mathematical modelling	*	N	B-C
95	Herrmann et al. (1994) - Humans Under Showers: Thermal Sensitivity, Thermoneutral Sensations, and Comfort Estimates	W	N	*	Case study; BU: End use data; Direct measurements	*	N	I
96	Ohnaka et al. (1994) - The effects of variation in body temperature on the preferred water temperature and flow rate during showering	W	N	*	Case study; BU: End use data; Direct measurements	*	N	I

Appendix B: Conference Paper

This appendix provides a copy of the conference paper from RO 1, a key outcome of this PhD that was not used in this thesis but included in this appendix for completion. The bibliographic details of the conference paper, including all authors, are:

Bors, J., Kenway, S., Lant, P., and Pamminger, F., 2014. *Temperature Variability in the Melbourne Water Network and the Impact on Residential Energy Use*. In Water, Energy and Climate Conference 2014: Solutions for Future Water Security, edited by International Water Association. Mexico City, Mexico: International Water Association.

Temperature Variability in the Melbourne Water Network and the Impact on Residential Energy Use

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Abstract
This paper describes the analytical methods used to estimate cold water temperature variability within a section of the Melbourne water distribution network. Cold water temperature is the thermal starting point for every household system using warm water. Consequently, knowing the cold water temperature is fundamental for quantifying water-related energy usage. Analysis of over 40,000 temperature records spanning 19 years demonstrated that water temperature could vary as much as 8°C within a 12 km^2 area in a single month. Additionally, the estimates from empirical data has identified that cold water temperature values presented in AS/NZS 4234:2008, '*Heated water systems – Calculation of energy consumption'*, can be improved.

Keywords
Water-related energy;

INTRODUCTION

The significance to greenhouse gas emissions of water-related energy in the residential sector has been previously identified. Water-related energy in Australian households contributes approximately 5% of national primary energy usage. Water temperature in the distribution network can significantly influence household energy usage and related greenhouse gas emissions. Preliminary sensitivity analysis, after the method of Kenway et al. (2013) demonstrated that a 10% change in the temperature of cold water (≈ 2°C change), influenced 0.3-0.7 kWh/hh.d household scale energy usage. This is equivalent to around 3-15% of water-related energy use or 3-5% of total household energy use (Kenway et al. 2013). The resultant impact on greenhouse gas emissions is in the order of 0.5-1.0 $kgCO_2$-e/hh.d for coal-fired electric water heating systems and 0.1-0.2 $kgCO_2$-e/hh.d for natural gas water heating systems (Kenway et al. 2013). Cold water temperature is the thermal starting point for every household system using water. Consequently, characterisation of cold water temperature is important in estimating water-related energy.

METHODS

Four methods were used to characterise the mean cold water temperature and standard deviation for five Melbourne households. The methods included (a) deriving the raw water temperature estimate from empirical data for: (i) the entire region, (ii) individual suburbs, (iii) the nearest / most upstream data point, and (b) estimating cold water temperature from air temperature data. Over 42,900 raw water temperature records from 1994-2013 and 961 locations across the Yarra Valley Water (YVW) distribution region were utilised. Online (continuous) water temperature data was sourced for three YVW locations and used to verify the raw water temperature dataset. Raw water temperature data, together with related infrastructure data were used to create time-based heat maps in ArcGIS v10.1 for monthly temperature profiles.

RESULTS AND DISCUSSION

The results of this study are as follows:

- Individual suburban subsets of raw water temperature data provided the most accurate mean cold water temperature estimates for the five Melbourne households.
- Online data indicated that individual pipes varied by up to 5°C on a daily basis while others exhibited minimal (<0.5°C) variation.
- There appeared to be a zone of warmer water geographically centred over inner city Melbourne (see Supplement).
- In certain cases, the water temperature varied as much as 8°C within a 12 km^2 area (see Supplement). Preliminary temporal analysis indicated that this variation is strongest in summer and relatively consistent over a six year period.
- Measured values identified that cold water temperature values presented in the AS/NZS 4234:2008, '*Heated water systems – Calculation of energy consumption*', can be improved.
- Preliminary analysis of the 42,900 data points indicated an upward trend in the raw water temperature recordings over the 19 year period. Further analysis is still required to determine what has caused this.

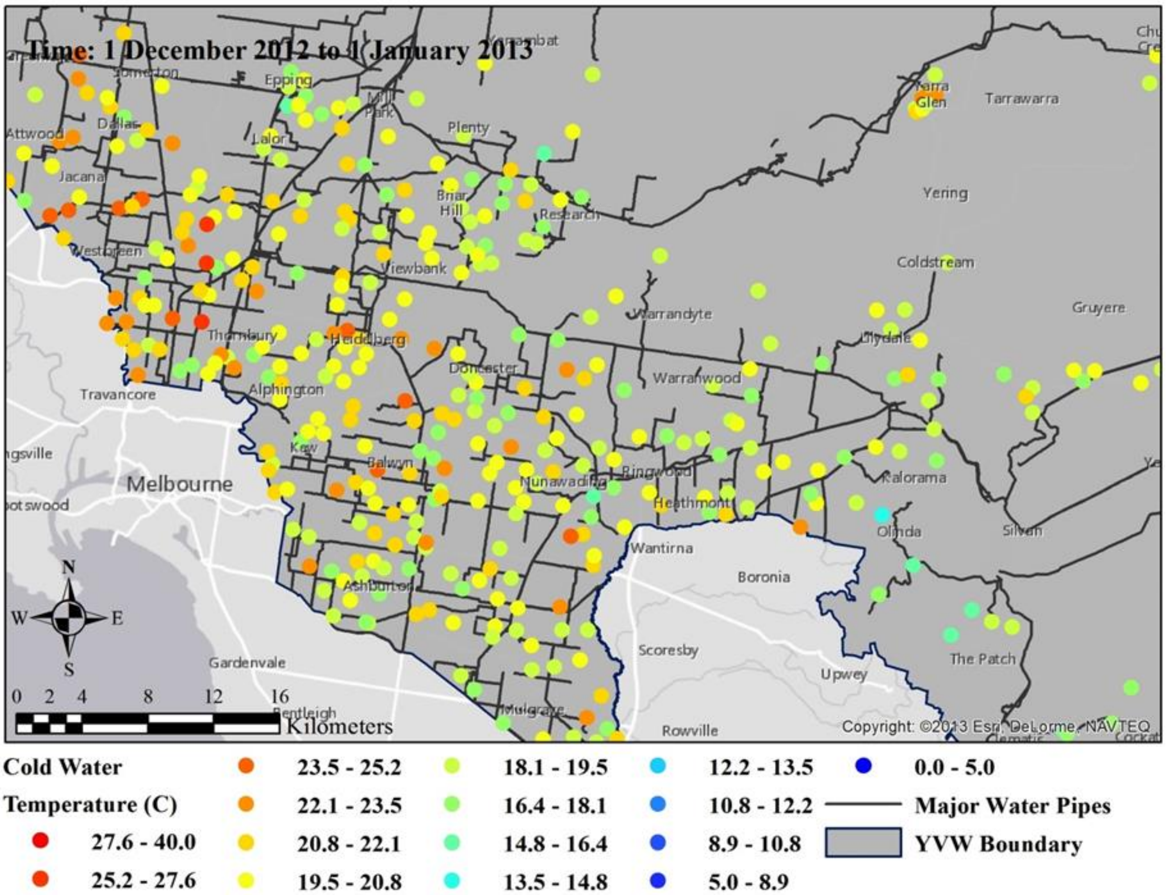
Characterising temperature in the water distribution system will assist in quantifying water-related energy at the household and city scale. It is likely that this work will assist in evaluating the performance of a range of hot water system types. Improved knowledge of temperature in the water system may also help to improve understanding of water quality changes, physical processes influencing the water asset and longer-term changes such as land use change or increased air temperature potentially associated with global warming.

CONCLUSION

Water, energy and carbon are more interrelated than has been previously recognised. Cold water temperature can have a significant impact on household energy usage therefore further knowledge is necessary in order to manage these effects. The study demonstrated the significant variation of cold water temperature within a section of Melbourne's water distribution network where the reticulated water temperature varied up to 8°C within a small area. There are wide-ranging and complex considerations involved in generating regional maps of reticulated water temperature for Melbourne which are critical in understanding water-related energy within households, associated greenhouse gas emissions and related costs.

REFERENCE

1. Kenway S.J., Scheidegger, R., Larson, T.A., Lant, P. & Bader, H.-P. 2013 Water-related energy in households: A model designed to understand the current state and simulate possible measures. *Energy and Buildings*, **58**, 378-389.



Reticulated water temperature variation within a section of the Melbourne water distribution network during December 2012

Appendix C: Chapter 3 Support Information

This appendix presents the support information for chapter 3 which addresses RO 1 of this thesis. Section C.1 lists the modelling assumptions and simplifications used to determine the impact of CWT variability on household WRE use. Section C.2 outlines the spatial statistics method that forms the basis of the *Hot Spot Analysis* tool (i.e. spatial statistics tool in ArcGIS) used to evaluate RO 1. Section C.3 provides the detailed *Hot Spot Analysis* results used to determine the zones of warmer and colder water supply.

C.1. Assumptions and Simplifications

- Simplification: The scale of spatial analysis was determined from the *Optimised Hot Spot Analysis* tool evaluation of the CWT measurement locations. This is the preferred method for choosing the spatial scale of analysis when the mechanism (i.e. the specific interaction between water infrastructure and the environment) causing CWT variability is unknown.
- Assumed the hot zone maximum CWT, cold zone minimum CWT and neutral zone average CWT provided reasonable boundaries of analysis for the CWT impact on household WRE.
- Assumed the behavioural, technological and environmental characteristics captured in the five Melbourne households study by Binks et al. [97] could be used for all households across the YVW distribution region.
    - This assumption was utilised as a means of theoretically assessing the impacts of CWT variation on residential energy use for the specified region.

C.2. Getis-Ord Local Statistic

This appendix section describes the spatial statistics behind the *Hot Spot Analysis* tool in ArcGIS 10.3. Details of Getis-Ord local statistic can be found in Getis and Ord [232] with the simplified calculation procedure presented below in *'How Hot Spot Analysis (Getis-Ord Gi*) works'* by Esri's online ArcGIS Resources webpage [233]. The Getis-Ord local statistic is given as:

Equation 3: $$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j}x_j - \bar{X}\sum_{j=1}^{n} w_{i,j}}{S\sqrt{\frac{\left[n\sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}$$

where x_j is the attribute value for feature *j*; $w_{i,j}$ is the spatial weight between feature *i* and *j*; *n* is equal to the total number of features. Thus,

Equation 4: $$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n}$$

Equation 5: $$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2}$$

The G_i^* statistic is a z-score.

C.3. Hot Spot Analysis

Table C-1 provides the monthly *Hot Spot Analysis* results for the variability in the CWT data. This data was used to determine the zones of warmer water supply, colder water supply and neutral zones. Table C-2 provides the recommended scale of spatial analysis determined from the measured CWT data using the *Optimised Hot Spot Analysis* tool in ArcGIS 10.3.

Table C-1: Monthly *Hot Spot Analysis (ArcGIS 10.3)* results for CWT variability within the YVW region, 2013.

Month	Zone	C.I.	##	Min T°C	Max T°C	Avge T°C	SD	Min Z-Score	Max Z-Score	Avge Z-Score	Min P-Value	Max P-Value	Avge P-Value
January	Cold Spot	99%	84	14.6	24.5	19.4	1.91	-6.293	-3.020	-4.473	0.000	0.003	0.000
		95%	8	17.1	21.4	19.5	1.71	-2.806	-2.350	-2.619	0.005	0.019	0.010
		90%	9	17.6	23.8	21.2	1.83	-2.276	-1.993	-2.217	0.023	0.046	0.027
	Not Significant		290	17.7	26.9	21.3	1.70	-1.989	1.944	0.304	0.047	0.992	0.525
	Hot Spot	90%	9	18.9	24.5	21.5	2.17	1.995	2.293	2.218	0.022	0.046	0.027
		95%	33	20.6	25.1	22.6	1.12	2.321	2.897	2.568	0.004	0.020	0.011
		99%	109	18.1	26.6	22.4	1.59	2.973	6.375	4.610	0.000	0.003	0.000
February	Cold Spot	99%	51	16.2	23.5	19.5	1.62	-5.795	-2.985	-4.623	0.000	0.003	0.000
		95%	7	15.4	24.5	20.8	2.93	-2.793	-2.461	-2.576	0.005	0.014	0.010
		90%	4	17	21.7	19.8	2.30	-2.282	-2.042	-2.197	0.022	0.041	0.029
	Not Significant		252	17.1	27.6	22.0	1.89	-2.016	1.927	0.200	0.044	0.987	0.389
	Hotspot	90%	18	20.4	25.8	22.4	1.38	2.032	2.336	2.147	0.019	0.042	0.033
		95%	21	18.7	25	22.6	1.81	2.355	2.929	2.610	0.003	0.019	0.010
		99%	91	19.2	27	23.2	1.72	2.963	6.186	4.649	0.000	0.003	0.000
March	Cold Spot	99%	39	16.8	23.3	19.5	1.58	-5.722	-2.978	-4.472	0.000	0.003	0.000
		95%	29	17.3	23.6	20.4	1.85	-2.882	-2.331	-2.647	0.004	0.020	0.009
		90%	9	19.4	22	20.7	1.00	-2.302	-1.993	-2.160	0.021	0.046	0.032
	Not Significant		241	17.8	25.2	21.5	1.63	-1.975	1.964	0.112	0.048	1.000	0.457
	Hotspot	90%	22	20.2	24.9	22.2	1.32	1.988	2.309	2.136	0.021	0.047	0.034
		95%	25	19.5	26.5	22.4	1.66	2.324	2.945	2.622	0.003	0.020	0.010
		99%	95	18.5	28.1	22.7	1.97	3.001	6.259	4.546	0.000	0.003	0.000
April	Cold Spot	99%	47	13.3	18.7	16.1	1.07	-6.879	-3.228	-5.548	0.000	0.001	0.000
		95%	41	15.1	19.6	17.4	1.16	-2.914	-2.294	-2.562	0.004	0.022	0.012
		90%	11	15.3	19.9	17.3	1.14	-2.269	-1.944	-2.131	0.023	0.052	0.034
	Not Significant		212	13.8	22.4	18.4	1.51	-1.790	1.904	0.486	0.057	0.997	0.440
	Hotspot	90%	39	15.5	22.2	18.8	1.60	1.909	2.268	2.086	0.023	0.056	0.038
		95%	45	15	21.8	18.7	1.52	2.273	2.980	2.562	0.003	0.023	0.012
		99%	91	16	22.6	19.1	1.26	3.012	5.669	4.317	0.000	0.003	0.000
May	Cold Spot	99%	54	11	15.8	13.5	1.15	-7.368	-2.962	-5.017	0.000	0.003	0.000
		95%	30	11.7	16.2	14.0	1.09	-2.860	-2.219	-2.444	0.004	0.027	0.016
		90%	5	14.2	16.1	15.0	0.84	-2.165	-1.903	-1.991	0.030	0.057	0.047
	Not Significant		213	11.9	18.1	15.1	1.28	-1.883	1.884	0.200	0.060	0.981	0.365
	Hotspot	90%	17	14.1	17.3	15.6	0.96	1.903	2.207	2.083	0.027	0.057	0.038
		95%	32	12.7	18.5	15.3	1.35	2.218	2.866	2.526	0.004	0.027	0.013
		99%	150	11.8	18.9	15.9	1.43	2.881	5.797	4.027	0.000	0.004	0.001
June	Cold Spo	99%	20	8.9	13.7	11.4	1.69	-4.904	-3.581	-4.464	0.000	0.000	0.000

		95%	15	9.3	14.3	11.5	1.55	-3.388	-2.645	-2.964	0.001	0.008	0.004
		90%	4	10.5	15.1	12.8	1.88	-2.555	-2.272	-2.459	0.011	0.023	0.015
	Not Significant		327	8.5	16.1	12.9	1.38	-2.234	2.221	0.509	0.025	1.000	0.352
	Hotspot	90%	27	11.8	14.8	13.3	0.93	2.247	2.602	2.393	0.009	0.025	0.017
		95%	40	11.6	15.6	13.3	1.02	2.623	3.449	3.024	0.001	0.009	0.003
		99%	2	13.6	13.7	13.6	0.07	3.647	3.685	3.666	0.000	0.000	0.000
July	**Cold Spot**	99%	40	7	12.1	10.9	0.80	-5.254	-3.048	-4.259	0.000	0.002	0.000
		95%	24	8.9	13	11.4	0.92	-2.954	-2.376	-2.554	0.003	0.017	0.012
		90%	15	10	12.9	11.3	0.85	-2.325	-1.989	-2.162	0.020	0.047	0.032
	Not Significant		276	7.6	15.1	11.9	0.95	-1.974	1.981	0.085	0.048	1.000	0.370
	Hotspot	90%	24	10.1	13.4	12.1	0.82	1.995	2.317	2.191	0.020	0.046	0.029
		95%	27	10.8	13.5	12.3	0.78	2.333	2.950	2.639	0.003	0.020	0.009
		99%	116	10.2	14.6	12.4	0.85	2.991	5.545	4.292	0.000	0.003	0.000
August	**Cold Spot**	99%	42	8.8	12.9	10.7	0.88	-5.804	-3.019	-4.426	0.000	0.003	0.000
		95%	20	10.5	14.2	11.3	0.80	-2.924	-2.392	-2.653	0.003	0.017	0.009
		90%	10	10	12.2	11.1	0.67	-2.274	-1.988	-2.111	0.023	0.047	0.036
	Not Significant		270	8.4	14.4	11.9	0.91	-1.938	1.977	0.366	0.048	0.998	0.426
	Hotspot	90%	40	10.2	14.1	12.3	1.01	1.991	2.319	2.156	0.020	0.046	0.032
		95%	39	10.3	14.1	12.0	1.00	2.356	2.993	2.581	0.003	0.018	0.011
		99%	90	10.1	14.8	12.4	0.86	3.036	5.067	4.109	0.000	0.002	0.000
September	**Cold Spot**	99%	33	8.7	14.6	12.9	1.36	-5.396	-3.082	-3.733	0.000	0.002	0.001
		95%	45	11.6	15.5	13.1	0.91	-2.984	-2.332	-2.674	0.003	0.020	0.009
		90%	16	12.3	16.3	13.5	1.05	-2.307	-2.002	-2.164	0.021	0.045	0.031
	Not Significant		249	10.4	17.9	14.0	1.13	-1.954	1.971	0.145	0.049	0.999	0.461
	Hotspot	90%	22	12	17.4	14.8	1.37	1.985	2.298	2.148	0.022	0.047	0.032
		95%	25	11.9	17.3	14.3	1.15	2.328	3.015	2.623	0.003	0.020	0.010
		99%	88	12.1	19	14.6	1.29	3.035	6.347	4.614	0.000	0.002	0.000
October	**Cold Spot**	99%	46	10	15.1	13.0	1.28	-5.518	-3.088	-3.886	0.000	0.002	0.000
		95%	52	11.3	16.9	13.8	1.36	-3.011	-2.291	-2.628	0.003	0.022	0.010
		90%	13	12.6	15.3	13.7	0.99	-2.261	-1.934	-2.188	0.024	0.053	0.029
	Not Significant		231	10.8	19.8	14.5	1.37	-1.873	1.921	0.301	0.055	0.997	0.437
	Hotspot	90%	24	12.2	16.9	14.9	1.33	1.934	2.256	2.109	0.024	0.053	0.036
		95%	60	12	17.6	15.0	1.23	2.274	3.014	2.650	0.003	0.023	0.009
		99%	82	11.9	19.1	15.0	1.38	3.030	5.179	3.768	0.000	0.002	0.001
November	**Cold Spot**	99%	44	11.5	19.7	14.4	2.13	-5.800	-3.171	-4.495	0.000	0.002	0.000
		95%	41	11.8	18	14.4	2.03	-2.956	-2.282	-2.590	0.003	0.022	0.011
		90%	9	12.3	19.9	15.6	2.87	-2.238	-1.960	-2.123	0.025	0.050	0.035
	Not Significant		205	12.3	24.2	15.9	2.05	-1.937	1.896	-0.018	0.053	0.999	0.427
	Hotspot	90%	12	12.1	20.4	16.8	2.37	1.996	2.268	2.158	0.023	0.046	0.032
		95%	33	12.6	21	17.3	1.65	2.281	2.962	2.561	0.003	0.023	0.012
		99%	73	11.8	22	17.3	2.06	2.995	6.295	4.850	0.000	0.003	0.000
December	**Cold Spot**	99%	107	11.2	22.1	15.7	2.88	-5.688	-2.927	-3.878	0.000	0.003	0.001
		95%	30	10.8	23.1	16.1	3.39	-2.828	-2.229	-2.540	0.005	0.026	0.013
		90%	10	12.4	21.6	15.7	3.40	-2.209	-1.924	-2.118	0.027	0.054	0.035
	Not Significant		191	11.2	22.2	17.0	2.53	-1.785	1.839	0.173	0.066	0.942	0.406
	Hotspot	90%	10	17.9	21.4	19.2	0.99	1.903	2.198	2.040	0.028	0.057	0.042
		95%	18	13.7	22.2	17.2	2.29	2.214	2.852	2.556	0.004	0.027	0.012
		99%	90	12.8	23.9	19.2	1.84	2.907	6.420	4.810	0.000	0.004	0.000

Table C-2: Recommended scale of spatial analysis for each month of 2013 from the *Optimised Hot Spot Analysis* tool in ArcGIS 10.3.

Month	Initial data assessment	Scale of spatial analysis
January	There are 542 valid input features. There were 7 outlier locations.	The optimal fixed distance band is based on the average distance to 27 nearest neighbors: 6430.00 m.
February	There are 444 valid input features. There were 8 outlier locations.	The optimal fixed distance band is based on the average distance to 22 nearest neighbors: 6399.00 m.
March	There are 460 valid input features. There were 10 outlier locations.	The optimal fixed distance band is based on the average distance to 23 nearest neighbors: 6540.00 m.
April	There are 486 valid input features. There were 10 outlier locations.	The optimal fixed distance band is based on the average distance to 24 nearest neighbors: 6393.00 m.
May	There are 501 valid input features. There were 15 outlier locations.	The optimal fixed distance band is based on the average distance to 25 nearest neighbors: 6479.00 m.
June	There are 435 valid input features. There were 7 outlier locations.	The optimal fixed distance band is based on the average distance to 21 nearest neighbors: 6442.00 m.
July	There are 522 valid input features. There were 13 outlier locations.	The optimal fixed distance band is based on the average distance to 26 nearest neighbors: 6488.00 m.
August	There are 511 valid input features. There were 7 outlier locations.	The optimal fixed distance band is based on the average distance to 25 nearest neighbors: 6373.00 m.
September	There are 478 valid input features. There were 13 outlier locations.	The optimal fixed distance band is based on peak clustering found at 5125.7941 Meters.
October	There are 508 valid input features. There were 11 outlier locations.	The optimal fixed distance band is based on the average distance to 25 nearest neighbors: 6378.0 m.
November	There are 417 valid input features. There were 6 outlier locations.	The optimal fixed distance band is based on peak clustering found at 5280.7229 Meters
December	There are 456 valid input features.2.8219. There were 6 outlier locations.	The optimal fixed distance band is based on the average distance to 22 nearest neighbors: 6373.00 m.

Appendix D: Chapter 4 Support Information

This appendix presents the support information for Chapter 4 which addresses RO 2 of this thesis. Section D.1 lists the general modelling assumptions and simplifications of the key determinants of household WRE use (i.e. household composition, HWS type, shower use and clothes washing use). These were used to model the residential WRE impact on regional water, WRE and associated emissions. Section D.2 provides details of the regional ResWE model simulation design and simulation process developed during this PhD. Section D.3 provides details of the calculation processes for key model parameters with specific assumptions and modelling simplifications including recommendations for future model improvement. Section D.4 lists the issues addressed during the verification data clean-up whilst section D.5 contains WRE use results for the base case of household WRE use for each of the 16 combinations of shower use and clothes washing use.

D.1. Assumptions and Simplifications

D.1.1. Household composition

- Assumed household composition and behaviour stayed the same throughout the period of analysis.
- Assumed all dwellings were occupied throughout the period of analysis.

D.1.2. HWS type

- Assumed each household composition group had the same proportion of HWS types without additional information.
- Simplification: medium water usage HWS types have been used.
  - This modelling simplification could be improved upon in future models by expanding the number of HWS sizes to accommodate each household composition type e.g. small HWSs for small households.
- Assumed each HWS was situated outside.
- Assumed the starting point temperature of each HWS was the average CWT from the mains water supply.
  - This assumption ignored the effects of surface pipe exposure to surface heat island temperatures on the basis that the volume of water contained within the pipe connection between the mains pipe and the HWS is small.
- Assumed that HWS technology stayed the same throughout the period of analysis.

D.1.3. Shower use

- Simplification: the same shower temperature was applicable for males and females and stayed consistent throughout the study period.
    - This modelling simplification can be improved upon in future models by sourcing separate temperature preferences for males and females.
- Assumed the shower temperature was the same for efficient and inefficient shower heads.
- Assumed frequency of shower use was consistent.
- Assumed shower duration did not change regardless of shower head efficiency.
- Assumed flowrates for adults and children were based on shower head efficiency.
- Assumed children also had low and high shower durations, the same as adult shower durations except for high shower use in winter.
- Assumed shower use technology, shower temperature, frequency, duration and flowrate stayed the same throughout the period of analysis.

D.1.4. Clothes washing use

- Simplification: frequency of clothes washing, and volume of clothes washing were seasonal without gradual adjustments between seasons.
    - This modelling simplification can be improved upon in future models by including a gradual change in clothes washing frequency and volume for transitional period of time between summer and winter seasons.
- Assumed clothes washing technology, frequency of use, load size and washing temperature stayed the same throughout the period of analysis.
- Simplification: hot wash cycle households (4%) and variable wash cycle households (19%) have been evaluated as warm wash cycle households.
    - There is the potential to underestimate or overestimate WRE use from this simplification. Future model improvements would include hot wash and variable wash cycle evaluation.

D.1.5. Future demographics

- Assumed occupancy rates stayed the same for each household composition type.
- Simplification: Reservoir split of family with children households (children under 15) and family without children households (no children under 15) in 2011 was valid for 2031 model prediction without additional information.

D.1.6. CWT

- Simplification: postcode boundaries were suitable for determining CWT averages.
  - This modelling simplification could be improved upon in future models by utilising the water utilities' water quality zones as the boundary for averaging monthly CWTs.
- Assumed CWT measurements within a specified month could be averaged to indicate the monthly average CWT without impacting the WRE use results.
  - It's important to note that CWT varies within a monthly cycle and diurnally within a day cycle, however, this type of temporal resolution is not available.

D.1.7. Data collection

- Assumed the data collected or aggregated to postcode scale has the same postcode boundary as the digital boundary sourced from the '*Australian Statistical Geography Standard (ASGS) Volume 3 - Non-ABS Structures (cat no. 1270.0.55.003)'*.

D.2. Regional ResWE Model

This appendix section provides details of the regional ResWE model simulation design and simulation process. Section D.2.1 contains tables describing the regional ResWE model simulation design developed for this PhD including household types, sample of input parameters, percentage of households for key parameters, and number of households for each household type. Section D.2.2 lists a step by step overview of the regional ResWE model simulation process including the creation of the input/output statistics files, the file conversions into the required formats, and an overview of the MATLAB files created to process the regional model outputs.

D.2.1. Regional ResWE model simulation design

Table D-1 details the 16 combinations of shower and clothes washing use that were utilised in this study to capture end use variability across a region. Table D-2 details the simulation layout of all 320 household types (i.e. 4 household compositions x 5 HWS types x 4 shower use x 4 clothes washing use). Table D-3 provides an example of the 145 input parameters required to model 1 of the 320 household types with references to input tables, calculation procedures and sources of data. Table D-4 outlines the percentage of households that contain key household technologies and behaviours that influence WRE across the study site. Table D-5 details the number of households in the study site that are modelled for each of the 320 household types used to quantify regional water, WRE and GHGs.

Table D-1: Summary of the 16 household types of shower use and clothes washing use.

Shower head type	Efficient				Inefficient			
Shower duration	Low		High		Low		High	
Clothes washer loading type	Top	Front	Top	Front	Top	Front	Top	Front
Households with warm wash cycle temperature	H1	H9	H3	H11	H5	H13	H7	H15
Households with cold wash cycle temperature	H2	H10	H4	H12	H6	H14	H8	H16

Table D-2: Breakdown of the regional ResWE model simulation process of the 320 household types (HT-1:320).[a]

	HC (1)	**HC (2)**	**HC (3)**	**HC (4)**
HWS (1)	**SIMULATION 1**	**SIMULATION 2**	**SIMULATION 3**	**SIMULATION 4**
	[HT-1] SU (1): CW (1)	[HT-17] SU (1): CW (1)	[HT-33] SU (1): CW (1)	[HT-49] SU (1): CW (1)
	[HT-2] SU (1): CW (2)	[HT-18] SU (1): CW (2)	[HT-34] SU (1): CW (2)	[HT-50] SU (1): CW (2)
	[HT-3] SU (2): CW (1)	[HT-19] SU (2): CW (1)	[HT-35] SU (2): CW (1)	[HT-51] SU (2): CW (1)
	[HT-4] SU (2): CW (2)	[HT-20] SU (2): CW (2)	[HT-36] SU (2): CW (2)	[HT-52] SU (2): CW (2)
	[HT-5] SU (3): CW (1)	[HT-21] SU (3): CW (1)	[HT-37] SU (3): CW (1)	[HT-53] SU (3): CW (1)
	[HT-6] SU (3): CW (2)	[HT-22] SU (3): CW (2)	[HT-38] SU (3): CW (2)	[HT-54] SU (3): CW (2)
	[HT-7] SU (4): CW (1)	[HT-23] SU (4): CW (1)	[HT-39] SU (4): CW (1)	[HT-55] SU (4): CW (1)
	[HT-8] SU (4): CW (2)	[HT-24] SU (4): CW (2)	[HT-40] SU (4): CW (2)	[HT-56] SU (4): CW (2)
	[HT-9] SU (1): CW (3)	[HT-25] SU (1): CW (3)	[HT-41] SU (1): CW (3)	[HT-57] SU (1): CW (3)
	[HT-10] SU (1): CW (4)	[HT-26] SU (1): CW (4)	[HT-42] SU (1): CW (4)	[HT-58] SU (1): CW (4)
	[HT-11] SU (2): CW (3)	[HT-27] SU (2): CW (3)	[HT-43] SU (2): CW (3)	[HT-59] SU (2): CW (3)

	HC (1)	HC (2)	HC (3)	HC (4)
	[HT-12] SU (2): CW (4)	[HT-28] SU (2): CW (4)	[HT-44] SU (2): CW (4)	[HT-60] SU (2): CW (4)
	[HT-13] SU (3): CW (3)	[HT-29] SU (3): CW (3)	[HT-45] SU (3): CW (3)	[HT-61] SU (3): CW (3)
	[HT-14] SU (3): CW (4)	[HT-30] SU (3): CW (4)	[HT-46] SU (3): CW (4)	[HT-62] SU (3): CW (4)
	[HT-15] SU (4): CW (3)	[HT-31] SU (4): CW (3)	[HT-47] SU (4): CW (3)	[HT-63] SU (4): CW (3)
	[HT-16] SU (4): CW (4)	[HT-32] SU (4): CW (4)	[HT-48] SU (4): CW (4)	[HT-64] SU (4): CW (4)
HWS (2)	**SIMULATION 5**	**SIMULATION 6**	**SIMULATION 7**	**SIMULATION 8**
	[HT-65] SU (1): CW (1)	[HT-81] SU (1): CW (1)	[HT-97] SU (1): CW (1)	[HT-113] SU (1): CW (1)
	[HT-66] SU (1): CW (2)	[HT-82] SU (1): CW (2)	[HT-98] SU (1): CW (2)	[HT-114] SU (1): CW (2)
	[HT-67] SU (2): CW (1)	[HT-83] SU (2): CW (1)	[HT-99] SU (2): CW (1)	[HT-115] SU (2): CW (1)
	[HT-68] SU (2): CW (2)	[HT-84] SU (2): CW (2)	[HT-100] SU (2): CW (2)	[HT-116] SU (2): CW (2)
	[HT-69] SU (3): CW (1)	[HT-85] SU (3): CW (1)	[HT-101] SU (3): CW (1)	[HT-117] SU (3): CW (1)
	[HT-70] SU (3): CW (2)	[HT-86] SU (3): CW (2)	[HT-102] SU (3): CW (2)	[HT-118] SU (3): CW (2)
	[HT-71] SU (4): CW (1)	[HT-87] SU (4): CW (1)	[HT-103] SU (4): CW (1)	[HT-119] SU (4): CW (1)
	[HT-72] SU (4): CW (2)	[HT-88] SU (4): CW (2)	[HT-104] SU (4): CW (2)	[HT-120] SU (4): CW (2)
	[HT-73] SU (1): CW (3)	[HT-89] SU (1): CW (3)	[HT-105] SU (1): CW (3)	[HT-121] SU (1): CW (3)
	[HT-74] SU (1): CW (4)	[HT-90] SU (1): CW (4)	[HT-106] SU (1): CW (4)	[HT-122] SU (1): CW (4)
	[HT-75] SU (2): CW (3)	[HT-91] SU (2): CW (3)	[HT-107] SU (2): CW (3)	[HT-123] SU (2): CW (3)
	[HT-76] SU (2): CW (4)	[HT-92] SU (2): CW (4)	[HT-108] SU (2): CW (4)	[HT-124] SU (2): CW (4)
	[HT-77] SU (3): CW (3)	[HT-93] SU (3): CW (3)	[HT-109] SU (3): CW (3)	[HT-125] SU (3): CW (3)
	[HT-78] SU (3): CW (4)	[HT-94] SU (3): CW (4)	[HT-110] SU (3): CW (4)	[HT-126] SU (3): CW (4)
	[HT-79] SU (4): CW (3)	[HT-95] SU (4): CW (3)	[HT-111] SU (4): CW (3)	[HT-127] SU (4): CW (3)
	[HT-80] SU (4): CW (4)	[HT-96] SU (4): CW (4)	[HT-112] SU (4): CW (4)	[HT-128] SU (4): CW (4)
HWS (3)	**SIMULATION 9**	**SIMULATION 10**	**SIMULATION 11**	**SIMULATION 12**
	[HT-129] SU (1): CW (1)	[HT-145] SU (1): CW (1)	[HT-161] SU (1): CW (1)	[HT-177] SU (1): CW (1)
	[HT-130] SU (1): CW (2)	[HT-146] SU (1): CW (2)	[HT-162] SU (1): CW (2)	[HT-178] SU (1): CW (2)
	[HT-131] SU (2): CW (1)	[HT-147] SU (2): CW (1)	[HT-163] SU (2): CW (1)	[HT-179] SU (2): CW (1)
	[HT-132] SU (2): CW (2)	[HT-148] SU (2): CW (2)	[HT-164] SU (2): CW (2)	[HT-180] SU (2): CW (2)
	[HT-133] SU (3): CW (1)	[HT-149] SU (3): CW (1)	[HT-165] SU (3): CW (1)	[HT-181] SU (3): CW (1)
	[HT-134] SU (3): CW (2)	[HT-150] SU (3): CW (2)	[HT-166] SU (3): CW (2)	[HT-182] SU (3): CW (2)
	[HT-135] SU (4): CW (1)	[HT-151] SU (4): CW (1)	[HT-167] SU (4): CW (1)	[HT-183] SU (4): CW (1)
	[HT-136] SU (4): CW (2)	[HT-152] SU (4): CW (2)	[HT-168] SU (4): CW (2)	[HT-184] SU (4): CW (2)
	[HT-137] SU (1): CW (3)	[HT-153] SU (1): CW (3)	[HT-169] SU (1): CW (3)	[HT-185] SU (1): CW (3)
	[HT-138] SU (1): CW (4)	[HT-154] SU (1): CW (4)	[HT-170] SU (1): CW (4)	[HT-186] SU (1): CW (4)
	[HT-139] SU (2): CW (3)	[HT-155] SU (2): CW (3)	[HT-171] SU (2): CW (3)	[HT-187] SU (2): CW (3)
	[HT-140] SU (2): CW (4)	[HT-156] SU (2): CW (4)	[HT-172] SU (2): CW (4)	[HT-188] SU (2): CW (4)
	[HT-141] SU (3): CW (3)	[HT-157] SU (3): CW (3)	[HT-173] SU (3): CW (3)	[HT-189] SU (3): CW (3)
	[HT-142] SU (3): CW (4)	[HT-158] SU (3): CW (4)	[HT-174] SU (3): CW (4)	[HT-190] SU (3): CW (4)
	[HT-143] SU (4): CW (3)	[HT-159] SU (4): CW (3)	[HT-175] SU (4): CW (3)	[HT-191] SU (4): CW (3)
	[HT-144] SU (4): CW (4)	[HT-160] SU (4): CW (4)	[HT-176] SU (4): CW (4)	[HT-192] SU (4): CW (4)
HWS (4)	**SIMULATION 13**	**SIMULATION 14**	**SIMULATION 15**	**SIMULATION 16**
	[HT-193] SU (1): CW (1)	[HT-209] SU (1): CW (1)	[HT-225] SU (1): CW (1)	[HT-241] SU (1): CW (1)
	[HT-194] SU (1): CW (2)	[HT-210] SU (1): CW (2)	[HT-226] SU (1): CW (2)	[HT-242] SU (1): CW (2)
	[HT-195] SU (2): CW (1)	[HT-211] SU (2): CW (1)	[HT-227] SU (2): CW (1)	[HT-243] SU (2): CW (1)
	[HT-196] SU (2): CW (2)	[HT-212] SU (2): CW (2)	[HT-228] SU (2): CW (2)	[HT-244] SU (2): CW (2)
	[HT-197] SU (3): CW (1)	[HT-213] SU (3): CW (1)	[HT-229] SU (3): CW (1)	[HT-245] SU (3): CW (1)
	[HT-198] SU (3): CW (2)	[HT-214] SU (3): CW (2)	[HT-230] SU (3): CW (2)	[HT-246] SU (3): CW (2)
	[HT-199] SU (4): CW (1)	[HT-215] SU (4): CW (1)	[HT-231] SU (4): CW (1)	[HT-247] SU (4): CW (1)
	[HT-200] SU (4): CW (2)	[HT-216] SU (4): CW (2)	[HT-232] SU (4): CW (2)	[HT-248] SU (4): CW (2)
	[HT-201] SU (1): CW (3)	[HT-217] SU (1): CW (3)	[HT-233] SU (1): CW (3)	[HT-249] SU (1): CW (3)
	[HT-202] SU (1): CW (4)	[HT-218] SU (1): CW (4)	[HT-234] SU (1): CW (4)	[HT-250] SU (1): CW (4)
	[HT-203] SU (2): CW (3)	[HT-219] SU (2): CW (3)	[HT-235] SU (2): CW (3)	[HT-251] SU (2): CW (3)
	[HT-204] SU (2): CW (4)	[HT-220] SU (2): CW (4)	[HT-236] SU (2): CW (4)	[HT-252] SU (2): CW (4)
	[HT-205] SU (3): CW (3)	[HT-221] SU (3): CW (3)	[HT-237] SU (3): CW (3)	[HT-253] SU (3): CW (3)
	[HT-206] SU (3): CW (4)	[HT-222] SU (3): CW (4)	[HT-238] SU (3): CW (4)	[HT-254] SU (3): CW (4)
	[HT-207] SU (4): CW (3)	[HT-223] SU (4): CW (3)	[HT-239] SU (4): CW (3)	[HT-255] SU (4): CW (3)
	[HT-208] SU (4): CW (4)	[HT-224] SU (4): CW (4)	[HT-240] SU (4): CW (4)	[HT-256] SU (4): CW (4)
HW	**SIMULATION 17**	**SIMULATION 18**	**SIMULATION 19**	**SIMULATION 20**

	HC (1)	HC (2)	HC (3)	HC (4)
	[HT-257] SU (1): CW (1)	[HT-273] SU (1): CW (1)	[HT-289] SU (1): CW (1)	[HT-305] SU (1): CW (1)
	[HT-258] SU (1): CW (2)	[HT-274] SU (1): CW (2)	[HT-290] SU (1): CW (2)	[HT-306] SU (1): CW (2)
	[HT-259] SU (2): CW (1)	[HT-275] SU (2): CW (1)	[HT-291] SU (2): CW (1)	[HT-307] SU (2): CW (1)
	[HT-260] SU (2): CW (2)	[HT-276] SU (2): CW (2)	[HT-292] SU (2): CW (2)	[HT-308] SU (2): CW (2)
	[HT-261] SU (3): CW (1)	[HT-277] SU (3): CW (1)	[HT-293] SU (3): CW (1)	[HT-309] SU (3): CW (1)
	[HT-262] SU (3): CW (2)	[HT-278] SU (3): CW (2)	[HT-294] SU (3): CW (2)	[HT-310] SU (3): CW (2)
	[HT-263] SU (4): CW (1)	[HT-279] SU (4): CW (1)	[HT-295] SU (4): CW (1)	[HT-311] SU (4): CW (1)
	[HT-264] SU (4): CW (2)	[HT-280] SU (4): CW (2)	[HT-296] SU (4): CW (2)	[HT-312] SU (4): CW (2)
	[HT-265] SU (1): CW (3)	[HT-281] SU (1): CW (3)	[HT-297] SU (1): CW (3)	[HT-313] SU (1): CW (3)
	[HT-266] SU (1): CW (4)	[HT-282] SU (1): CW (4)	[HT-298] SU (1): CW (4)	[HT-314] SU (1): CW (4)
	[HT-267] SU (2): CW (3)	[HT-283] SU (2): CW (3)	[HT-299] SU (2): CW (3)	[HT-315] SU (2): CW (3)
	[HT-268] SU (2): CW (4)	[HT-284] SU (2): CW (4)	[HT-300] SU (2): CW (4)	[HT-316] SU (2): CW (4)
	[HT-269] SU (3): CW (3)	[HT-285] SU (3): CW (3)	[HT-301] SU (3): CW (3)	[HT-317] SU (3): CW (3)
	[HT-270] SU (3): CW (4)	[HT-286] SU (3): CW (4)	[HT-302] SU (3): CW (4)	[HT-318] SU (3): CW (4)
	[HT-271] SU (4): CW (3)	[HT-287] SU (4): CW (3)	[HT-303] SU (4): CW (3)	[HT-319] SU (4): CW (3)
	[HT-272] SU (4): CW (4)	[HT-288] SU (4): CW (4)	[HT-304] SU (4): CW (4)	[HT-320] SU (4): CW (4)

[a] Refer to Chapter 4, Table 4-2 for significant parameter abbreviations.

Table D-3: Source of input parameters required to run the regional ResWE model.

P#	Unit	Description	Value	Source
Parameters for the household				
P1	[-]	Number of adults per household	Table 4-3	[178], Table B25; section D.3.1
P2	[-]	Number of children per household	Table 4-3	
P3	[°C]	Temperature cold water	Table 4-7	[191]; section D.3.5.1
P4	[°C]	Temperature hot water at HWS	Table 4-4	[187]; [234]; [235]
P5	[°C]	Average indoor temperature	Table 4-7	[197]; section D.3.5.2
P6	[°C]	Ambient air temperature at HWS storage	Table 4-7	[192]; section D.3.5.3
P7	[m]	Ave. length of wastewater pipes	9.00	[69][a]
P8	[m/s]	Velocity of wastewater	0.14	[69][a]
P9	[m]	Radius of wastewater pipe	0.07	[69][a]
P10	[W/m²°K]	Heat coefficient of wastewater pipe	2.00	[69][a]
P11	[m]	Average length of hot-water pipes (storage to tap)	9.40	[69][a]
P12	[m/s]	Velocity of hot water	1.70	[69][a]
P13	[m]	Radius of hot-water pipe	0.01	[188][a]
P14	[W/m²°K]	Heat coefficient of hot-water pipe	2.00	[69][a]
P15	[W/m²°K]	Heat coefficient of hot-water storage	0.50	[69][a]
P16	[m²]	Surface of hot water storage	Table 4-4	[184]; [185]; [188]; section D.3.2.2
P17	[-]	Split of hot water storage: share of gas use	Table 4-4	N/A
P18	[-]	Number of stand times in hot water pipes	2.69	[69][a]
P19	[m]	Thickness of hot-water pipe	0.001	[69][a]
P20	[-]	Switch: hws standard (0) / solar heat (1)	0 or 1	N/A
P21	[-]	Share of solar hot water on total hw	Table 4-7	[236]; [198], Tables 7 & 9; section D.3.5.4D.3.5.4
P22	[-]	Part of hot water continuous system for total hot water	Balance of P21	
P23	[-]	share of gas use for continuous hw system	0 or 1	N/A
End use 1: Parameters for shower use, section D.3.3				
P24	[min]	Flow duration per shower for adults	Table 4-5	[114], Table 7.1
P25	[L/min]	Flowrate per showers for adults	Table 4-5	[114], Table 7.3 & p.25; [115], Table 6.1
P26	[-]	Number of showers per adult per day	0.90	[114], Table 7.4
P27	[°C]	Temperature of showers for adults	38.64	[69][a]
P28	[min]	Flow duration per shower for child	Table 4-5	[114], Table 7.3 & p.25

P29	[L/min]	Flowrate per showers for child	Table 4-5	[114], Table 7.3 & p.25; [115], Table 6.1
P30	[-]	Number of showers per child per day	0.29	[69][a]
P31	[°C]	Temperature of showers for child	35.50	[69][a]
P32	[-]	Fraction of instantaneous shower heating	0.00	N/A
P33	[-]	Split of instant. Shower: share of gas use	0.00	N/A
End use 2: Parameters for bath use				
P34	[L]	Volume per bath per adult	0.00	[69][a]
P35	[-]	Number of baths per adult per day	0.00	[69][a]
P36	[°C]	Temperature of baths for adults	0.00	[69][a]
P37	[L]	Volume per bath per child	89.28	[69][a]
P38	[-]	Number of baths per child per day	0.36	[69][a]
P39	[°C]	Temperature of baths for child	37.00	[69][a]
P40	[-]	Fraction of instantaneous bath heating	0.00	N/A
P41	[-]	Split of instant. Bath share of gas use	0.00	N/A
End use 3: Parameters for clothes washing use, section D.3.4				
P42	[-]	Number of cycles cold top per day	Table 4-6	[183], Fig. 16 & p.26
P43	[-]	Number of cycles warm top per day	Table 4-6	[183], Fig. 16 & p.26
P44	[-]	Number of cycles hot top per day	0.00	N/A
P45	[-]	Number of cycles cold front per day	Table 4-6	[183], Fig. 16 & p.26
P46	[-]	Number of cycles warm front per day	Table 4-6	[183], Fig. 16 & p.26
P47	[-]	Number of cycles hot front per day	0.00	N/A
P48	[L]	Volume per cycle cold top	Table 4-6	[199], Table 13
P49	[L]	Volume per cycle warm top	Table 4-6	[199], Table 13
P50	[L]	Volume per cycle hot top	0.00	N/A
P51	[L]	Volume per cycle cold front	Table 4-6	[199], Table 13
P52	[L]	Volume per cycle warm front	Table 4-6	[199], Table 13
P53	[L]	Volume per cycle hot front	0.00	N/A
P54	[kWh]	Energy per cycle cold top (excl. water heating)	Table 4-6	[186]
P55	[kWh]	Energy per cycle warm top (excl. water heating)	Table 4-6	[186]
P56	[kWh]	Energy per cycle hot top (excl. water heating)	0.00	N/A
P57	[kWh]	Energy per cycle cold front (excl. water heating)	Table 4-6	[186]
P58	[kWh]	Energy per cycle warm front (excl. water heating)	Table 4-6	[186]
P59	[kWh]	Energy per cycle hot front (excl. water heating)	0.00	N/A
P60	[°C]	Temperature cold cycle top	P3	[191][b]
P61	[°C]	Temperature warm cycle top	Table 4-6	[63]
P62	[°C]	Temperature hot cycle top	0.00	N/A
P63	[°C]	Temperature cold cycle front	Table 4-6	[63]
P64	[°C]	Temperature warm cycle front	Table 4-6	[63]
P65	[°C]	Temperature hot cycle front	0.00	N/A
P66	[min]	Duration average cycle top	Table 4-6	[186]; section D.3.4
P67	[min]	Duration average cycle front	Table 4-6	[186]; section D.3.4
P68	[W]	Standby energy top	Table 4-6	[69][a]
P69	[W]	Standby energy front	Table 4-6	[69][a]
P70	[-]	Connected to hot+cold (0) or only cold (1) water	Table 4-6	[186]; section D.3.4
End use 4: Parameters for tap use				
P71	[-]	Number hand wash per person per day	3.93	[69], max calibration
P72	[L]	Volume per hand wash	1.40	[69], max calibration
P73	[°C]	Temperature hand wash	P3	[191][b]
P74	[-]	Number teeth brush per person per day	2.00	[69], max calibration
P75	[L]	Volume teeth brush	2.46	[69][a]
P76	[°C]	Temperature teeth brush	P3	[191][b]
P77	[-]	Number shave per adult per day	0.92	[69], max calibration
P78	[L]	Volume per shave	2.50	[69], max calibration
P79	[°C]	Temperature shave	P3	[191][b]
P80	[-]	Number dish wash (by hand) per hh per day	0.96	[69][a]
P81	[L]	Volume dish wash (by hand)	8.57	[69][a]
P82	[°C]	Temperature dish wash (by hand)	50.24	[69][a]

P83	[-]	Number clothes wash (by hand) per hh per day	0.08	[69][a]
P84	[L]	Volume per clothes wash (by hand)	14.00	[69][a]
P85	[°C]	Temperature clothes wash (by hand)	38.00	[69][a]
P86	[-]	Number cleaning per hh per day	0.07	[69][a]
P87	[L]	Volume per cleaning	10.95	[69][a]
P88	[°C]	Temperature of cleaning	39.72	[69][a]
P89	[-]	Number other use per person per day	Table D-9	[116]; section D.3.6.1
P90	[L]	Volume other use	1.40	[116]
P91	[°C]	Temperature other use	P3	[191]
P92	[-]	Fraction of instantaneous tap water heating	0.00	N/A
P93	[-]	Split of instant. Taps share of gas use	0.00	N/A
End use 5: Parameters for dishwasher use				
P94	[-]	Number of cycles dishwasher per day	Table D-10	[183], Fig. 20; section D.3.6.2
P95	[L]	Volume per cycle dishwasher	12.52	[69][a]
P96	[kWh]	Energy per cycle dishwasher (excl. water heating)	0.72	[69][a]
P97	[°C]	Temperature dishwasher cycle	58.33	[69][a]
P98	[min]	Duration average cycle dishwasher	100.33	[69][a]
P99	[W]	Standby energy dishwasher	2.20	[69][a]
P100	[-]	Connected to hot+cold (0) or only cold (1) water	1.00	[69][a]
End use 6: Parameters for outdoor use				
P101	[L]	Pool volume per day	0.00	N/A
P102	[L]	Irrigation per day	Table 4-7	[199], Fig. 6; [230]; [193]; section D.3.5.5
P103	[min]	Duration pool filtration per day	0.00	N/A
P104	[kW]	Power of pool filter	0.00	N/A
End use 7: Parameters for toilet use				
P105	[-]	Number of toilet flushes per person per day	3.93	[69], max calibration
P106	[L]	Volume per toilet flush	4.43	[69], max calibration
End use 8: Parameters per kettle use				
P107	[-]	Number of kettle boils per person per day	1.51	[69][a]
P108	[L]	Volume per boil	0.76	[69][a]
End use 9: Parameters for air-conditioning use				
P109	[L/min]	Water use aircon evap.	1.10	[69][a]
P110	[min]	Duration use aircon evap.	Table 4-7	[69][a]; [200], Table 11; [201], Table 5; section D.3.5.6
P111	[W]	Energy used aircon evap.	843.00	[69][a]
P112	[W]	Standby energy aircon evap.	2.00	[63]
P113	[min]	Duration use aircon rest	0.00	N/A
P114	[W]	Energy used aircon rest	0.00	N/A
P115	[W]	Standby energy aircon rest	0.00	N/A
End use 10: Parameters for other energy use				
P116	[min]	Duration use cooking	64.47	[69], max calibration
P117	[W]	Energy used cooking	7385.80	[69], 90th per. calibration
P118	[W]	Standby energy cooking	3.20	[69][a]
P119	[min]	Duration use fridge	1440.00	[69][a]
P120	[W]	Energy used fridge	66.82	[69][a]
P121	[W]	Standby energy fridge	0.00	N/A
P122	[min]	Duration use TV	171.25	[69][a]
P123	[W]	Energy used TV	201.64	[69][a]
P124	[W]	Standby energy TV	3.28	[69][a]
P125	[min]	Duration use light	3723.50	[69][a]
P126	[W]	Energy used light	32.11	[69][a]
P127	[W]	Standby energy light	0.00	[69][a]
P128	[min]	Duration use PC	786.55	[69][a]
P129	[W]	Energy used PC	60.70	[69][a]

P130	[W]	Standby energy PC	4.60	[69][a]
P131	[min]	Duration use heating	Table 4-7	[69]; [200], Table 9; section D.3.5.7
P132	[W]	Energy used heating	7576	[69][a]
P133	[W]	Standby energy heating	2.20	[69][a]
P134	[-]	Split of cooking energy: share of gas use	0.91	[69][a]
P135	[-]	Split of heating energy: share of gas use	1.00	[69], max calibration
Parameters for supply				
P136	[-]	Efficiency fact. for hw storage electrical	1.0204	[63]
P137	[-]	Efficiency fact. for hw storage gas	1.3106	[63]
P138	[-]	Efficiency fact. for instant. hw gas	0.00	N/A
P139	[-]	Efficiency fact. for hw cloth washer	1.05	[69]
P140	[-]	Efficiency fact. for hw dish washer	1.05	[69]
P141	[-]	Efficiency fact. for hw kettle boil	1.05	[69]
P142	[-]	Efficiency fact. for heating water outdoor pool	1.05	[69]
p143	[-]	Efficiency fact. for instant. hw electrical	0.00	N/A
p144	[-]	Efficiency fact. for hw continuous electrical	0.00	N/A
p145	[-]	Efficiency fact. for hw continuous gas	1.5385	[63]

[a] Average of input parameters for Melbourne households ($n=5$) in Binks et al. [69]. [b] Assumed temperature is equal to cold water supply temperature, parameter P3.

Table D-4: Percentage breakdown of households for key factors influencing household WRE.[a]

Household composition	**%**	**Source**	**HWS type**	**%**	**Source**
HC (1)	23	[178], Table B25	**HWS (1)**	10	[179], Table 3a
HC (2)	44	[178], Table B25	**HWS (2)**	56	[179], Table 3a; [190], Table 5.2.1.1
HC (3)	29	[178], Table B25	**HWS (3)**	30	[179], Table 31; [190], Table 5.2.1.1
HC (4)	5	[178], Table B25	**HWS (4)**	2	[179], Table 3a; [180], Table 3.12
-	-	-	**HWS (5)**	2	[179], Table 3a; [180], Table 3.12
Shower use	**%**	**Source**	**Clothes washing use**	**%**	**Source**
SU (1)	11	[182], Table 14; [181], Table 18	**CW (1)**	22	[179], Table 13a; [183], Table 17
SU (2)	10	[182], Table 14; [181], Table 18	**CW (2)**	47	[179], Table 13a; [183], Table 17
SU (3)	41.5	Assume balance of efficient shower heads; [181], Table 18	**CW (3)**	10	[179], Table 13a; [183], Table 17
SU 4)	37.5	Assume balance of efficient shower heads; [181], Table 18	**CW (4)**	21	[179], Table 13a; [183], Table 17

[a] Refer to Chapter 4, Table 4-2 for significant parameter abbreviations.

Table D-5: Number of households for each of the 320 household types (HT) in Reservoir.

	HC (1)	**HC (2)**	**HC (3)**	**HC (4)**
HWS (1)	**SIMULATION 1**	**SIMULATION 2**	**SIMULATION 3**	**SIMULATION 4**
	[HT-1] 11.6	[HT-17] 21.9	[HT-33] 14.4	[HT-49] 2.4
	[HT-2] 25.2	[HT-18] 47.6	[HT-34] 31.2	[HT-50] 5.1
	[HT-3] 10.5	[HT-19] 19.8	[HT-35] 13.0	[HT-51] 2.1
	[HT-4] 22.8	[HT-20] 43.1	[HT-36] 28.3	[HT-52] 4.6
	[HT-5] 43.6	[HT-21] 82.4	[HT-37] 54.0	[HT-53] 8.9
	[HT-6] 94.9	[HT-22] 179.1	[HT-38] 117.5	[HT-54] 19.3
	[HT-7] 39.5	[HT-23] 74.5	[HT-39] 48.9	[HT-55] 8.0
	[HT-8] 85.9	[HT-24] 162.1	[HT-40] 106.3	[HT-56] 17.5
	[HT-9] 5.2	[HT-25] 9.8	[HT-41] 6.4	[HT-57] 1.1

	HC (1)	HC (2)	HC (3)	HC (4)
	[HT-10] 11.3	[HT-26] 21.4	[HT-42] 14.0	[HT-58] 2.3
	[HT-11] 4.7	[HT-27] 8.9	[HT-43] 5.8	[HT-59] 1.0
	[HT-12] 10.2	[HT-28] 19.3	[HT-44] 12.7	[HT-60] 2.1
	[HT-13] 19.6	[HT-29] 37.0	[HT-45] 24.3	[HT-61] 4.0
	[HT-14] 42.6	[HT-30] 80.4	[HT-46] 52.8	[HT-62] 8.7
	[HT-15] 17.7	[HT-31] 33.5	[HT-47] 21.9	[HT-63] 3.6
	[HT-16] 38.6	[HT-32] 72.8	[HT-48] 47.7	[HT-64] 7.8
HWS (2)	**SIMULATION 5**	**SIMULATION 6**	**SIMULATION 7**	**SIMULATION 8**
	[HT-65] 62.6	[HT-81] 118.2	[HT-97] 77.5	[HT-113] 12.7
	[HT-66] 136.2	[HT-82] 257.0	[HT-98] 168.6	[HT-114] 27.7
	[HT-67] 56.7	[HT-83] 106.9	[HT-99] 70.1	[HT-115] 11.5
	[HT-68] 123.2	[HT-84] 232.5	[HT-100] 152.5	[HT-116] 25.1
	[HT-69] 235.6	[HT-85] 444.6	[HT-101] 291.7	[HT-117] 47.9
	[HT-70] 512.4	[HT-86] 966.8	[HT-102] 634.2	[HT-118] 104.2
	[HT-71] 213.2	[HT-87] 402.3	[HT-103] 263.9	[HT-119] 43.4
	[HT-72] 463.6	[HT-88] 874.7	[HT-104] 573.8	[HT-120] 94.3
	[HT-73] 28.1	[HT-89] 53.1	[HT-105] 34.8	[HT-121] 5.7
	[HT-74] 61.1	[HT-90] 115.4	[HT-106] 75.7	[HT-122] 12.4
	[HT-75] 25.4	[HT-91] 48.0	[HT-107] 31.5	[HT-123] 5.2
	[HT-76] 55.3	[HT-92] 104.4	[HT-108] 68.5	[HT-124] 11.3
	[HT-77] 105.8	[HT-93] 199.6	[HT-109] 130.9	[HT-125] 21.5
	[HT-78] 230.0	[HT-94] 434.0	[HT-110] 284.7	[HT-126] 46.8
	[HT-79] 95.7	[HT-95] 180.6	[HT-111] 118.5	[HT-127] 19.5
	[HT-80] 208.1	[HT-96] 392.7	[HT-112] 257.6	[HT-128] 42.3
HWS (3)	**SIMULATION 9**	**SIMULATION 10**	**SIMULATION 11**	**SIMULATION 12**
	[HT-129] 33.6	[HT-145] 63.5	[HT-161] 41.6	[HT-177] 6.8
	[HT-130] 73.1	[HT-146] 138.0	[HT-162] 90.5	[HT-178] 14.9
	[HT-131] 30.4	[HT-147] 57.4	[HT-163] 37.7	[HT-179] 6.2
	[HT-132] 66.2	[HT-148] 124.9	[HT-164] 81.9	[HT-180] 13.5
	[HT-133] 126.5	[HT-149] 238.8	[HT-165] 156.6	[HT-181] 25.7
	[HT-134] 275.2	[HT-150] 519.2	[HT-166] 340.6	[HT-182] 56.0
	[HT-135] 114.5	[HT-151] 216.0	[HT-167] 141.7	[HT-183] 23.3
	[HT-136] 248.9	[HT-152] 469.8	[HT-168] 308.2	[HT-184] 50.6
	[HT-137] 15.1	[HT-153] 28.5	[HT-169] 18.7	[HT-185] 3.1
	[HT-138] 32.8	[HT-154] 62.0	[HT-170] 40.6	[HT-186] 6.7
	[HT-139] 13.7	[HT-155] 25.8	[HT-171] 16.9	[HT-187] 2.8
	[HT-140] 29.7	[HT-156] 56.1	[HT-172] 36.8	[HT-188] 6.0
	[HT-141] 56.8	[HT-157] 107.2	[HT-173] 70.3	[HT-189] 11.6
	[HT-142] 123.5	[HT-158] 233.1	[HT-174] 152.9	[HT-190] 25.1
	[HT-143] 51.4	[HT-159] 97.0	[HT-175] 63.6	[HT-191] 10.5
	[HT-144] 111.8	[HT-160] 210.9	[HT-176] 138.4	[HT-192] 22.7
HWS (4)	**SIMULATION 13**	**SIMULATION 14**	**SIMULATION 15**	**SIMULATION 16**
	[HT-193] 2.1	[HT-209] 3.9	[HT-225] 2.6	[HT-241] 0.4
	[HT-194] 4.5	[HT-210] 8.5	[HT-226] 5.6	[HT-242] 0.9
	[HT-195] 1.9	[HT-211] 3.5	[HT-227] 2.3	[HT-243] 0.4
	[HT-196] 4.1	[HT-212] 7.7	[HT-228] 5.0	[HT-244] 0.8
	[HT-197] 7.8	[HT-213] 14.7	[HT-229] 9.6	[HT-245] 1.6
	[HT-198] 16.9	[HT-214] 31.9	[HT-230] 20.9	[HT-246] 3.4
	[HT-199] 7.0	[HT-215] 13.3	[HT-231] 8.7	[HT-247] 1.4
	[HT-200] 15.3	[HT-216] 28.9	[HT-232] 18.9	[HT-248] 3.1
	[HT-201] 0.9	[HT-217] 1.8	[HT-233] 1.1	[HT-249] 0.2
	[HT-202] 2.0	[HT-218] 3.8	[HT-234] 2.5	[HT-250] 0.4
	[HT-203] 0.8	[HT-219] 1.6	[HT-235] 1.0	[HT-251] 0.2
	[HT-204] 1.8	[HT-220] 3.4	[HT-236] 2.3	[HT-252] 0.4

	HC (1)	HC (2)	HC (3)	HC (4)
	[HT-205] 3.5	[HT-221] 6.6	[HT-237] 4.3	[HT-253] 0.7
	[HT-206] 7.6	[HT-222] 14.3	[HT-238] 9.4	[HT-254] 1.5
	[HT-207] 3.2	[HT-223] 6.0	[HT-239] 3.9	[HT-255] 0.6
	[HT-208] 6.9	[HT-224] 13.0	[HT-240] 8.5	[HT-256] 1.4
HWS (5)	**SIMULATION 17**	**SIMULATION 18**	**SIMULATION 19**	**SIMULATION 20**
	[HT-257] 2.4	[HT-273] 4.5	[HT-289] 2.9	[HT-305] 0.5
	[HT-258] 5.1	[HT-274] 9.7	[HT-290] 6.4	[HT-306] 1.0
	[HT-259] 2.1	[HT-275] 4.0	[HT-291] 2.6	[HT-307] 0.4
	[HT-260] 4.7	[HT-276] 8.8	[HT-292] 5.8	[HT-308] 0.9
	[HT-261] 8.9	[HT-277] 16.8	[HT-293] 11.0	[HT-309] 1.8
	[HT-262] 19.3	[HT-278] 36.5	[HT-294] 23.9	[HT-310] 3.9
	[HT-263] 8.0	[HT-279] 15.2	[HT-295] 10.0	[HT-311] 1.6
	[HT-264] 17.5	[HT-280] 33.0	[HT-296] 21.7	[HT-312] 3.6
	[HT-265] 1.1	[HT-281] 2.0	[HT-297] 1.3	[HT-313] 0.2
	[HT-266] 2.3	[HT-282] 4.4	[HT-298] 2.9	[HT-314] 0.5
	[HT-267] 1.0	[HT-283] 1.8	[HT-299] 1.2	[HT-315] 0.2
	[HT-268] 2.1	[HT-284] 3.9	[HT-300] 2.6	[HT-316] 0.4
	[HT-269] 4.0	[HT-285] 7.5	[HT-301] 4.9	[HT-317] 0.8
	[HT-270] 8.7	[HT-286] 16.4	[HT-302] 10.7	[HT-318] 1.8
	[HT-271] 3.6	[HT-287] 6.8	[HT-303] 4.5	[HT-319] 0.7
	[HT-272] 7.9	[HT-288] 14.8	[3HT-04] 9.7	[HT-320] 1.6

D.2.2. Regional ResWE model simulation process

The step by step simulation process behind the regional ResWE model used to evaluate regional water, WRE and GHGs for the study site is listed below. See the supplementary '*Modelling Folder'* for sample modelling files.

- Created 240 sets of input statistics (i.e. Excel Worksheets), where one set of input statistics contained ResWE model input data for 16 household types for one month of analysis, thus 12 input worksheets were required for 12 months of analysis for each set of 16 household types. There were 2,336 input parameters for each of the 240 Excel Worksheets e.g. '*Sim1AprIn.xlxs4*'.
- Converted the 240 input statistic Excel Worksheets into Text Documents e.g. '*Sim1AprIn.txt4*'.
- Ran the 240 input statistics Text Documents through the regional ResWE model in SIMBOX and generated 240 output statistics STA Files e.g. '*Sim1AprOut4.sta'*. ResWE is a mathematical material flow analysis model developed through a collaboration between A/Prof Steven Kenway and Eawag, Swiss Federal Institute of Aquatic Science and Technology. MMFA framework development can be found in Eawag et al. [237].
- Extracted 240 output statistics Text Documents from the STA Files. There were 4,539 output parameters for each output statistic Text Document containing data outputs for 16 out of 320 household types e.g. *'Sim1AprOut4.txt'*.

- Converted the output statistics Text Documents into Excel Worksheets for scenario analysis e.g. *'Sim1AprOut4.xlxs'*.
- Created a MATLAB code file to import data from the Excel Worksheets, i.e. *'importfile.m'*.
- Created a MATLAB code file to extract monthly totals of regional water use, wastewater flow, electricity use, and gas use for each month of analysis using *'importfile.m'*. Example code file *'GenAprOut4File.m'* was used to create regional water, wastewater and energy totals for the month of April in a separate file e.g. *'AprOut4'*.
- During the calibration process, empirical data was plotted against the model data as an interim check for model verification e.g. *'MeasuredData'* for empirical data file, *'Plot4File.m'* for generating graphs, and the sample graph *'GenOut4Plot.pdf'*.
- Exported each months MATLAB data file to an Excel Worksheet for model verification graphs e.g. *'AprOut4Total.xlxs'*.

D.3. Model Calculation Process for Key ResWE Model Parameters

This appendix section provides details of the sources of data and calculation processes involved for key ResWE model input parameters as well as the process for determining the number of households for each household type (i.e. 4 household compositions x 5 HWS types x 4 shower use variations x 4 clothes washing use variations). Sections D.3.1 to D.3.4 outlines the end use variability within households across the study site whilst section D.3.5 outlines the variability in environmental parameters and weather-related end use activities. Section D.3.6 outlines key processes for other parameters in this study. Section D.3.1 provides support information for household composition and occupancy rates found in Table 4-3. Section D.3.2 provides support information for HWS characteristics found in Table 4-4. Sections D.3.3 and D.3.4 provide support information for shower use and clothes washing use found in Table 4-5 and Table 4-6, respectively. Section D.3.5 provide support information for environmental parameters (i.e. CWT, indoor air temperature, ambient air temperature and solar fractions) and weather-related end uses (i.e. irrigation, space cooling and space heating) found in Table 4-7.

D.3.1. Household composition

Household composition defining key household occupancy rates, parameters P1 & P2, were determined from ABS census data for the study site. A summary of household composition characteristics was presented in Chapter 4, Table 4-3.

- Households were grouped into 4 main types: (i) family with children, (ii) family without children, (iii) single, and (iv) group households.
  - Simplification: family with children households referred to dual parent and single parent family households with children under 15 years of age.
    - This modelling simplification helped to ascertain the resource consumption impact of children in households.
  - Simplification: family without children households included: couple households, dual parent family households with young adults that are 15 years of age or older, single parent family households with young adults that are 15 years of age or older, and other family households.
    - This modelling simplification could be improved upon in future models by expanding the number of household composition types.
- The number of families and the number of persons in families with children under 15 was sourced from the ABS [178], Table B25. The same process was applied to families without children, single and group households.

- Proportions of the four household composition types compared with total ABS households for Reservoir was evaluated. The same process was applied to number of persons in each household composition type.
- SA1 level measured water use data [193] used for model verification determined the number of households that were included whilst SA1 level census data [230] determined the number of people included in this study.
- Proportions of the 4 household composition types and the proportions of people in each household composition type derived from ABS census data were used to characterise the available measured water use households.

D.3.2. Hot water systems

D.3.2.1. HWS types

HWSs used in the study site were sourced from ABS household energy use data and a Victorian household survey. A summary of HWS characteristics was presented in Chapter 4, Table 4-4.

- HWSs were grouped into 5 main types: (i) electric with storage, (ii) gas with storage, (iii) continuous gas, (iv) electric-boosted solar, and (v) gas-boosted solar.
- The percentage breakdown of the energy source for HWSs by labour force region was the basis for determining electric, gas or solar HWS usage in the study site, sourced from ABS [179], Table 3a.
- Breakdown of storage vs continuous GHWSs by region was sourced from a Department of Health and Human Services report [190], Table 5.2.1.1, and applied to the percentage share of GHWSs.
- Breakdown of electric vs gas boosted SHWSs was sourced from ABS [180], Table 3.12, and applied to the percentage share of SHWSs.

D.3.2.2. HWS storage

The surface area for storage tank heat loss, parameter P16, was evaluated from storage tank dimensions for each HWS type with hot water storage. HWSs found in Australia were sourced from an electric water heater dataset [184], a gas water heater dataset [185], and a solar system product specification [188], values presented in Chapter 4, Table 4-4.

- Utilised an online water heater finder to ascertain the most suitable hot water storage tank sizes for medium water usage in medium sized households across the study site (Table D-6 and Table D-7).

Table D-6: Criteria for storage capacity requirements of medium usage electric SHWSs, source: [238].

Criteria	
Postcode	3073
Gas type	Electric
No. of bedrooms	3
No. of bathrooms	2
Water usage	Medium
Results	
Off peak electric storage capacity	125-160 L
Electric-boosted solar, storage capacity	200-250 L

Table D-7: Criteria for storage capacity requirements of medium usage gas SHWSs, source: [238].

Criteria	
Postcode	3073
Gas type	Gas
No. of bedrooms	3
No. of bathrooms	2
Water usage	Medium
Results	
Gas storage capacity	135-170 L
Gas-boosted solar, storage capacity	175-330 L

- For each hot water storage tank size selected, tank dimensions were sourced from an electric water heater dataset [184], a gas water heater dataset [185] and solar systems product specification sheet [188].
- Surface area for storage tank heat loss was evaluated from tank dimensions specified in Table D-8.
  - Assumed each hot water storage tank was cylindrical in shape and heat loss occurred from the main surface only. Potential heat loss from the top and bottom of the hot water cylinder were considered negligible.
  - Simplification: both electric-boosted and gas-boosted SHWSs were split systems with a ground level storage system booster (i.e. storage boosters heat all the water in the tank when the temperature drops).

Table D-8: Surface area of each HWS type for heat loss evaluation.

HWS type	Storage tank volume (L)	Width (mm)	Height (mm)	Surface (m^2)	Source
Electric storage	160[a]	515	1530	2.47	[184]
Gas storage	135[a]	420	1604	2.12	[185]
Electric-boosted solar	250	620	1515	2.58	[188]
Gas-boosted solar	250	1325	1515	2.58	[188]

[a] Sustainability Victoria notes that "*electric hot water storage systems require a larger storage capacity than gas units to provide the same amount of hot water*", therefore a larger storage tank size was chosen for medium usage electric storage systems than medium usage gas storage systems [239].

D.3.3. Shower use

Shower use household types used in this study were sourced from a Melbourne appliance stock survey report, and ABS water use data. Shower use parameters P24-P33 were sourced from Melbourne water end use reports and household scale WRE study. A summary of shower use characteristics was presented in Chapter 4, Table 4-5.

- There were four main shower use types considered. Shower use technology consisted of an: (i) efficient, or (ii) inefficient shower head. Shower use behaviour consisted of either: (i) low, or (ii) high shower duration.
- Breakdown of households categorised with either efficient or inefficient shower heads in YVW were sourced from Ghobadi et al. [182], Table 14.
- Breakdown of households categorised as either low or high shower duration were sourced from ABS water conservation data [181], Table 18.
- Average flowrate for an efficient shower head in the study site was sourced from Roberts et al. [115], Table 6.1, and the average capacity flowrate for an inefficient shower head was sourced from Redhead et al. [114], Table 7.3 & p25.
- Average flowrate for high shower duration was taken to be one standard deviation above the YVW mean flowrate, sourced from Redhead et al. [114], Table 7.1, with different flowrates evaluated for summer and winter shower use.
    - Assumed the summer flowrates were applicable during warmer months of January-April, November and December whilst the winter flowrates were applicable during cooler months of May-October.
    - The average flowrate for low shower duration was assumed to be the widely prescribed 4-minute shower during both summer and winter.
        - The 4-minute shower modelling simplification enabled the evaluation of potential WRE savings from the shower use scenarios using the initial modelling results. This modelling simplification could be improved upon in future models by evaluating lower shower duration as one standard deviation below the average mean shower duration in the base model, then evaluating potential WRE savings with the 4-minute shower scenario.
- Average shower use frequency for adults in Melbourne was sourced from Redhead et al. [114], Table 7.4 and average shower use frequency for children was sourced from Binks et al. [69].
- Average shower use temperature for both adults and children was sourced from Binks et al. [69].

D.3.4. Clothes washing use

Clothes washing use household types used in this study were sourced from an ABS appliance dataset and a Melbourne appliance stock survey report. Clothes washing parameters P42-P70 were sourced from a Melbourne appliance stock survey report, Melbourne water end use report, clothes washer dataset, CWT dataset and household scale study on WRE. A summary of clothes washing use characteristics was presented in Chapter 4, Table 4-6.

- There were four main clothes washing use types considered. Clothes washing use technology consisted of either a: (i) front loader, or (ii) top loader clothes washer household. Clothes washing use behaviour consisted of either: (i) warm wash, or (ii) cold wash temperature household.
- Breakdown of households categorised with either a front loader or top loader clothes washer was sourced from ABS [179], Table 13a.
- Breakdown of households categorised with either a warm wash or cold wash cycle was sourced from Roberts et al. [183], Table 17.
- Frequency of clothes washing use per day, was calculated for each household composition type on a household basis by using a clothes washing usage equation for the study site sourced from Roberts et al. [183], Figure 16. Thus,

Equation 6: P42, P43, P45 & P46 = $(2.225*(P1+P2)^{0.691})/7$

  - Household composition based clothes washing frequency in Table D-9.

Table D-9: Clothes washing use frequency for each household composition type.

<table>
<tr><th colspan="3">ResWE model</th><th colspan="4">Household composition</th></tr>
<tr><th>P#</th><th>Units</th><th>Description</th><th>Group</th><th>Family with children</th><th>Family without children</th><th>Single</th></tr>
<tr><td>P42</td><td>[-]</td><td>Number of cycles cold top per day</td><td rowspan="4">0.36</td><td rowspan="4">0.35</td><td rowspan="4">0.34</td><td rowspan="4">0.32</td></tr>
<tr><td>P43</td><td>[-]</td><td>Number of cycles warm top per day</td></tr>
<tr><td>P45</td><td>[-]</td><td>Number of cycles cold front per day</td></tr>
<tr><td>P46</td><td>[-]</td><td>Number of cycles warm front per day</td></tr>
</table>

- Wash cycle volume for both front loader and top loader clothes washers during summer and winter in YVW were sourced from Gan et al. [199], Table 13.
  - Assumed the summer volumes were applicable during warmer months of January-April, November and December whilst the winter volumes were applicable during cooler months of May-October.
- Top loader cold wash cycle temperature was sourced from YVW [193] whilst all other wash cycle temperatures were sourced from Flower [63].

- Step 7: Average wash cycle duration for front loaders and top loaders was sourced from E3 [186].
- Energy per wash cycle temperature (excluding water heating) for each clothes washer type was sourced from E3 [186]. Standby energy for each clothes washer type was sourced from Binks et al. [69].
- The clothes washer connection to either the electricity grid or the HWS was sourced from E3 [186].

D.3.5. Environmental parameters and weather-related end uses

D.3.5.1. CWT

The 119 CWT readings for Reservoir 2013, parameter P3, were extracted from a 66,068 CWT measurement dataset provided by YVW [191]. A summary of average monthly CWT readings was presented in Chapter 4, Table 4-7.

- Monthly averages of CWT were processed from the data subset.
  - Assumed the average monthly temperature of CWT readings within the study site boundary would be applicable as the water supply temperature input parameter P3 for all households across the study site.
  - Assumed the average monthly CWT would be applicable for all input parameters that use cold tap water e.g. temperature of hand washing, P73 etc.
    - This modelling simplification could underestimate WRE for households that use warm water for tap use activities such as teeth brushing. Future model improvements could source preferred temperatures for tap use activities.

D.3.5.2. Average indoor temperature

The average indoor air temperature, parameter P5, was sourced from Commonwealth Scientific and Industrial Research Organisation [197] and presented in Chapter 4, Table 4-7.

- Applied each of the average summer and winter season values for indoor temperature across a 6-month period.
  - Assumed the summer indoor temperature value was applicable during warmer ambient air temperature and CWT months of January-April, November and December. Assumed the winter indoor temperature value was applicable during cooler ambient air temperature and CWT months of May-October.

D.3.5.3. Ambient air temperature

The average monthly ambient air temperature readings for Reservoir 2013, parameter P6, were processed from a 3 hourly air temperature observation dataset (≈32,584 observations) sourced from BOM [192]. A summary of average monthly ambient air temperatures was presented in Chapter 4, Table 4-7.

- Geographical coordinates for weather stations close to the study site were sourced from BOM and mapped using ArcGIS to assess the weather station proximity to the study site.
- Essendon Airport (#86038) was chosen because: (i) it was the closest weather station to the study site with a mostly complete set of 3 hourly ambient air temperature readings for 2013 (≈2,920 observations), and (ii) it visually presented similar vegetation cover to the study site.
- Average daily air temperatures were evaluated from the 3 hourly temperature readings, then average monthly air temperatures were evaluated from the average daily air temperatures within each month for 2013.
    - Assumed the daily averages used to calculate monthly averages would provide a reasonable temperature reading for evaluating water end use activities that interact with ambient air temperature in the ResWE model.
        - This modelling simplification could be improved upon in future models by using ambient air temperature observations during peak water end use activity time i.e. observations before 9am and after 4pm.

D.3.5.4. Solar fraction

The solar fractions for electric-boosted and gas-boosted SHWSs, parameter P21, were evaluated from the monthly solar energy delivered to each HWS storage tank and the auxiliary energy required for medium sized solar systems. Thus,

Equation 7: $P21_{month}$ = Total Solar Energy Delivered to Storage (kWh/month) / Total Energy Delivered to Storage (kWh/month)

where Total Energy Delivered to Storage (kWh) is the sum of Solar Energy and Auxiliary Energy, both delivered to the SHWS storage tank. A summary of monthly solar fractions was presented in Chapter 4, Table 4-7.

- Used an online solar energy calculator to determine the monthly electricity output for medium usage SHWSs in Reservoir [236].
    - Calculations used average sunlight data (between 1990-2017) sourced from BOM [236].

- Estimated the monthly auxiliary energy for medium sized solar systems using a water heater energy use report sourced from the Victorian Sustainability Energy Authority [198], Tables 7 & 9.
  - Auxiliary energy included storage tank heat loss, standby energy of the instantaneous booster of the split system and fans.
- Evaluated the monthly solar fraction using collected data and Equation 7.
  - Assumed the energy for the solar pump in a split system SHWS was negligible at 1% of total energy input [240].
  - Average solar fraction of 51% compared with estimated Melbourne solar fractions of 50-62% sourced from Crawford et al. [100, 211].

D.3.5.5. Irrigation

Garden irrigation for each household per day, parameter P102, was calculated by converting average irrigation per person data sourced from a Melbourne water end use report to average irrigation per household, values presented in Chapter 4, Table 4-7.

- Average irrigation rate per person was sourced from Gan et al. [199], Figure 6, and converted to per household using SA1 level measured water use data [193] which determined the number of households and SA1 level census data [230] which determined the number of people included in this study.
  - Assumed all households participated in an equal amount of irrigation.
    - This modelling simplification can be improved upon in future models by re-examining irrigation rates for different dwelling types.
- Number of months used for irrigation was sourced from Gan et al. [199].
  - Assumed irrigation rates gradually increased to a peak in January then gradually decreased. Annual irrigation rates using this method was within 94% of annual irrigation rates using household scale measured irrigation data for the study site sourced from Binks et al. [69].

D.3.5.6. Space cooling

The amount of time spent using air conditioning in each household per day, parameter P110, was sourced from Binks et al. [69] and ABS [200, 201], values presented in Chapter 4, Table 4-7.

- Average air conditioning rate was sourced from Binks et al. [69] and average number of months used for household air conditioning was sourced from ABS [200, 201], Table 11 & Table 5.

- Assumed air conditioning rates gradually increased to a peak in January then gradually decreased. Annual air conditioning rates using this method was within 99% of annual air conditioning rates using household scale measured air conditioning data for the study site sourced from Binks et al. [69].

D.3.5.7. Space heating

The amount of time spent heating each household per day, parameter P132, was sourced from Binks et al. [69] and ABS [200], values presented in Chapter 4, Table 4-7.

- Average household heating rate was sourced from Binks et al. [69] and average number of months spent heating was sourced from ABS [200], Table 9.
  - Assumed heating rates gradually increased to a peak in July then gradually decreased. Annual heating rates using this method was within 140% of annual heating rates using household scale measured heating data for the study site sourced from Binks et al. [69].

D.3.6. Other parameters

D.3.6.1. Tap use

Frequency of ‘other’ tap use per day, parameter P89, was calculated for each household composition type on a per person basis by using frequency of total tap use data sourced from a YVW water end use report minus other tap use events in the ResWE model. Thus,

Equation 8: $P89 = 19.6^{a} - P71 - P74 - P77 - P83/(P1+P2) - P86/(P1+P2)$

- [a] Frequency of total tap use sourced from Athuraliya et al. [116].
- ‘Other’ tap use events for each household composition type presented in Table D-10.
- Assumed household water leaks were included in ‘other’ tap use.

Table D-10: Number of ‘other’ tap use events for each household composition type.

ResWE model			Household composition			
P#	**Units**	**Description**	**Group**	**Family with children**	**Family without children**	**Single**
P89	[-]	Number of other use per person per day	12.58	12.43	12.25	11.52

D.3.6.2. Dishwasher use

Frequency of dishwasher use per day, parameter P94, was calculated for each household composition type on a household basis by using a dishwasher usage equation for the study site sourced from Roberts et al. [183], Figure 20. Thus,

Equation 9: $P94 = (1.706*(P1+P2)^{0.623})/7$

- Dishwasher use for each household composition type presented in Table D-11.

Table D-11: Number of dishwasher use events for each household composition type.

ResWE model			Household composition			
P#	**Units**	**Description**	**Group**	**Family with children**	**Family without children**	**Single**
P94	[-]	Number of cycles dishwasher per day	0.79	0.53	0.40	0.23

D.4. Verification Data Clean-up

D.4.1. Measured water use data

The 234,243 water use meter readings for Reservoir were extracted from a 1,048,575 water use meter reading dataset provided by YVW [193]. This dataset required the following clean-up tasks to be of use as a source for calibrating the predictive ResWE water use model:

- Multiple water use addresses (e.g. different street addresses) for a singular meter reading needed to be resolved.
- Overlapping meter reading dates between each quarter for individual locations needed to be resolved (e.g. first quarter meter reading would end after second quarter meter reading had already begun thus providing two completely different water use frequencies for the one location during the overlapping dates).
- Irregular meter readings for a considerable number of water use addresses needed to be resolved (e.g. some locations would have a water meter reading once a year instead of every quarter).
- Resolving irregular water use meter readings (e.g. some meter readings were several orders of magnitude over or under the average water use readings and needed to be individually assessed).

D.5. ResWE Model Results for Households

Table D-12 provides estimates of the WRE consumption variability of shower use and clothes washing use technology and behaviour choices between household composition types. These results provide an overview of low to very high WRE use for the study site which falls into the 3rd decile of the 2011 Index of Relative Advantage and Disadvantage, 2nd decile of the Index of Economic Resources, and 5th decile of the Index of Education and Occupation [177].

Table D-12: WRE use characterisation (average kWh/p.d) of the 16 shower use and clothes washing use configurations for each household composition type.

WRE Use	**H#**	**Shower use**		**Clothes washing**		**Household composition**			
		Shower head	**Shower duration**	**Clothes washer**	**Wash cycle**	**Group**	**Family with children**	**Family without children**	**Single**
Low	**H2**	Efficient	Short	Top	Cold	1.1 ±0.3	1.5 ±0.4	1.5 ±0.5	2.3 ±0.9
	H10	Efficient	Short	Front	Cold	1.3 ±0.3	1.7 ±0.4	1.7 ±0.5	2.6 ±0.9
	H6	Inefficient	Short	Top	Cold	1.6 ±0.5	1.9 ±0.6	2.0 ±0.6	2.8 ±1.1
	H9	Efficient	Short	Front	Warm	1.6 ±0.2	2.0 ±0.4	2.1 ±0.4	3.2 ±0.8
Moderate	**H14**	Inefficient	Short	Front	Cold	1.8 ±0.5	2.1 ±0.6	2.2 ±0.6	3.1 ±1.1
	H4	Efficient	Long	Top	Cold	2.2 ±0.7	2.2 ±0.7	2.6 ±0.8	3.4 ±1.2
	H1	Efficient	Short	Top	Warm	1.8 ±0.5	2.3 ±0.7	2.4 ±0.7	3.5 ±1.2
	H13	Inefficient	Short	Front	Warm	2.1 ±0.5	2.4 ±0.6	2.6 ±0.6	3.6 ±1.0
High	**H12**	Efficient	Long	Front	Cold	2.4 ±0.7	2.4 ±0.7	2.8 ±0.8	3.7 ±1.2
	H5	Inefficient	Short	Top	Warm	2.3 ±0.7	2.6 ±0.8	2.9 ±1.0	4.0 ±1.4
	H11	Efficient	Long	Front	Cold	2.7 ±0.6	2.8 ±0.6	3.2 ±0.8	4.3 ±1.1
	HH3	Efficient	Long	Top	Warm	2.9 ±0.9	3.0 ±0.9	3.5 ±1.1	4.6 ±1.5
Very High	**H8**	Inefficient	Long	Top	Cold	3.8 ±1.3	3.3 ±1.1	4.2 ±1.4	5.0 ±1.7
	H16	Inefficient	Long	Front	Cold	3.9 ±1.3	3.4 ±1.1	4.4 ±1.4	5.3 ±1.7
	H15	Inefficient	Long	Front	Warm	4.2 ±1.3	3.8 ±1.0	4.7 ±1.4	5.8 ±1.7
	H7	Inefficient	Long	Top	Warm	4.7 ±1.5	4.0 ±1.3	5.1 ±1.7	6.1 ±2.1

Appendix E: Chapter 5 Support Information

This appendix presents the support information for Chapter 5 which addresses RO 3. Section E.1, Table E-1 provides the spatial scale legend for Table E-2 which provides examples of the spatial and temporal scales of available data investigated during regional ResWE model development. Section E.2, Table E-3 provides an example attribute table of the major water infrastructure pipes loaded into the WRE geodatabase.

E.1. Spatial and Temporal Scales of Available Data

Table E-1: Spatial scale legend for examples of regional ResWE model data inputs, Table E-2.

Data table legend	
Spatial scale	Description
HH	Household
MB	Mesh Block
SA1	Statistical Area Level 1
SA2	Statistical Area Level 2
SA3	Statistical Area Level 3
SA4	Statistical Area Level 4
SSC	State Suburbs
POA	Postal Areas
YVW	Yarra Valley Water Business Boundary
SR	Statistical Region
State	State
Aus.	Australia/National
	Indirect parameter information found

Table E-2: Examples of the available spatial and temporal scales of the regional ResWE model data inputs.

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
P1	[-]	Number of adults per household				✓	✓	✓	✓	✓			✓	✓	Census Data, Community Profiles [176]	2011
					✓	✓	✓	✓	✓	✓			✓	✓	TableBuilder Pro, Census Data [230]	2011
	[-]	*Number of people per dwelling*		✓											2074.0 - Census of Population and Housing: Mesh Block Counts [209]	2011
P2	[-]	Number of children per household				✓	✓	✓	✓	✓			✓	✓	Census Data, Community Profiles [176]	2011
					✓	✓	✓	✓	✓	✓			✓	✓	TableBuilder Pro, Census Data [230]	2011
	[-]	*Number of people per dwelling*		✓											2074.0 - Census of Population and Housing: Mesh Block Counts [209]	2011
P3	[°C]	Temperature cold water				✓				✓					YVW Temperature Data 1995 to 2013	Jan 2006 – May 2013
P17	[-]	Split of HWS: share of gas use										✓			Table 3a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
P21	[min]	Flow duration per shower for adults														
	[min]	*Average duration per shower for all hh members*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[min]	*Average duration per shower for all hh members*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P22	[l/min]	Flowrate per showers for adults														
	[l/min]	*Standard shower flow rate; 3 Star shower flow rate; All showers flow rate for all hh members*									✓				Table 4-3, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[l/min]	*Standard shower flow rate; 3 Star shower flow rate; All showers flow rate for all hh members*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
	[l/p/day]	*Shower end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[-]	*No. & proportion of hh per type of shower head per age of dwelling*											✓	✓	Table 15, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P23	[-]	Number of showers per adult per day														
	[-]	*Frequency of showering for all hh members*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[-]	*Proportion of hh with children under 10 and corresponding frequency of showering*									✓				Table 4-4, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average
	[-]	*Frequency of showering for all hh members*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
	[-]	*Proportion of hh with children under 10 and corresponding frequency of showering*									✓				Table 6-2, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P25	[min]	Flow duration per shower for child														
	[min]	*Average duration per shower for all hh members*									✓				Table 4-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average, 2004
	[min]	*Average duration per shower for all hh members*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P26	[l/min]	Flowrate per showers for child														
	[l/min]	*Standard shower flow rate; 3 Star shower flow rate; All showers flow rate for all hh members*									✓				Table 4-3, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average

Parameter			Spatial scale												Data source	Temporal scale
No.	Unit	Description	HH	MB	SA1	SA2	SA3	SA4	SSC	POA	YVW	SR	State	Aus.		
	[l/min]	*Standard shower flow rate; 3 Star shower flow rate; All showers flow rate for all hh members*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
	[l/p/day]	*Shower end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[-]	*No. & proportion of hh per type of shower head per age of dwelling*											✓	✓	Table 15, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P27	[-]	Number of showers per child per day														
	[-]	*Frequency of showering for all hh members*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[-]	*Proportion of hh with children under 10 and corresponding frequency of showering*									✓				Table 4-4, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average
	[-]	*Frequency of showering for all hh members*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
	[-]	*Proportion of hh with children under 10 and corresponding frequency of showering*									✓				Table 6-2, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P31	[l]	Volume per bath per adult														
	[l]	*Average volume of bath per hh member*									✓				p39, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
	[l/p/day]	*Bath end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[-]	*No. & proportion of hh per source of water for bathing or showering*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P32	[-]	Number of baths per adult per day														

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[-/wk]	*Average number of baths per week (bath users) per hh member*									✓				Figure 4-19, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average
	[-/wk]	*Average number of baths per week (bath users) per hh member*									✓				Figure 6-19, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-/wk]	*Average number of baths per week (all hh) per hh member*									✓				Figure 6-19, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Proportion of combined bath & shower share of indoor use*									✓				Table 6-9, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P34	[l]	Volume per bath per child														
	[l]	*Average volume of bath per hh member*									✓				p39, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
	[l/p/day]	*Bath end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[-]	*No. & proportion of hh per source of water for bathing or showering*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P35	[-]	Number of baths per child per day														
	[-/wk]	*Average number of baths per week (bath users) per hh member*									✓				Figure 4-19, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average
	[-/wk]	*Average number of baths per week (bath users) per hh member*									✓				Figure 6-19, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-/wk]	*Average number of baths per week (all hh) per hh member*									✓				Figure 6-19, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Proportion of combined bath & shower share of indoor use*									✓				Table 6-9, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P39	[-]	Number cycles cold top per day														

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[-/wk]	*Number cycles top per week [no temp]*											✓		Table 15a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[-]	*Proportion of hh with top loader*											✓	✓	Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*Proportion of hh with a washing machine*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh using cold wash*											✓	✓	Supplementary file, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
	[-]	*No. & proportion of hh per source of water for washing clothes*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P40	[-]	Number cycles warm top per day														
	[-/wk]	*Number cycles top per week [no temp]*											✓		Table 15a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[-]	*Proportion of hh with top loader*											✓	✓	Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*Proportion of hh with a washing machine*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh using warm wash*											✓	✓	Supplementary file, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
	[-]	*No. & proportion of hh per source of water for washing clothes*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P41	[-]	Number cycles hot top per day														

Parameter			Spatial scale												Data source	Temporal scale
No.	Unit	Description	HH	MB	SA1	SA2	SA3	SA4	SSC	POA	YVW	SR	State	Aus.		
	[-/wk]	*Number cycles top per week [no temp]*											✓		Table 15a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[-]	*Proportion of hh with top loader*											✓	✓	Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*Proportion of hh with a washing machine*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh using hot wash*											✓	✓	Supplementary file, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
	[-]	*No. & proportion of hh per source of water for washing clothes*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P42	[-]	Number cycles cold front per day														
	[-/wk]	*Number cycles front per week [no temp]*											✓		Table 15a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[-]	*Proportion of hh with front loader*											✓	✓	Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*Proportion of hh with a washing machine*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh using cold wash*											✓	✓	Supplementary file, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
	[-]	*No. & proportion of hh per source of water for washing clothes*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
P43	[-]	Number cycles warm front per day														
	[-/wk]	*Number cycles front per week [no temp]*											✓		Table 15a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[-]	*Proportion of hh with front loader*											✓	✓	Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*Proportion of hh with a washing machine*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh using warm wash*											✓	✓	Supplementary file, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh per source of water for washing clothes*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P44	**[-]**	Number cycles hot front per day														
	[-/wk]	*Number cycles front per week [no temp]*											✓		Table 15a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[-]	*Proportion of hh with front loader*											✓	✓	Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*Proportion of hh with a washing machine*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[-]	*No. & proportion of hh using hot wash*											✓	✓	Supplementary file, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
	[-]	*No. & proportion of hh per source of water for washing clothes*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [200]	2013

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
P45	[l]	Volume per cycle cold top														
	[l]	*Average volume per top loader*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average volume per top loader*									✓				Table 6-6, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P46	[l]	Volume per cycle warm top														
	[l]	*Average volume per top loader*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average volume per top loader*									✓				Table 6-6, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P47	[l]	Volume per cycle hot top														
	[l]	*Average volume per top loader*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average volume per top loader*									✓				Table 6-6, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P48	[l]	Volume per cycle cold front														
	[l]	*Average volume per front loader*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average volume per front loader*									✓				Table 6-6, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P49	[l]	Volume per cycle warm front														
	[l]	*Average volume per front loader*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average volume per front loader*									✓				Table 6-6, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P50	[l]	Volume per cycle hot front														

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[l]	*Average volume per front loader*									✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average volume per front loader*									✓				Table 6-6, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P68	[-]	Number hand wash per person per day														
	[-]	*Average number of tap uses per day*									✓				Table 6-7, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Distribution of tap use duration*									✓				Figure 6-16, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P69	[l]	Volume per hand wash														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P71	[-]	Number teeth brush per person per day														
	[-]	*Average number of tap uses per day*									✓				Table 6-7, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Distribution of tap use duration*									✓				Figure 6-16, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P72	[l]	Volume teeth brush														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P74	[-]	Number shave per adult per day														

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[-]	*Average number of tap uses per day*									✓				Table 6-7, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Distribution of tap use duration*									✓				Figure 6-16, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P75	[l]	Volume per shave														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P77	[-]	Number dish wash (by hand) per hh per day														
	[-]	*Average number of tap uses per day*									✓				Table 6-7, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Distribution of tap use duration*									✓				Figure 6-16, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P78	[l]	Volume dish wash (by hand)														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P80	[-]	Number clothes wash (by hand) per hh per day														
	[-]	*Average number of tap uses per day*									✓				Table 6-7, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Distribution of tap use duration*									✓				Figure 6-16, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
P81	[l]	Volume per cloth wash (by hand)														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P83	[-]	Number cleaning per hh per day														
	[-]	*Average number of tap uses per day*									✓				Table 6-7, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
	[-]	*Distribution of tap use duration*									✓				Figure 6-16, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
P84	[l]	Volume cleaning														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P87	[l]	Volume other use														
	[l/p/day]	*Unidentified end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
P91	[-]	Number cycles dish washer per day											✓		Table 17a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
											✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
											✓				Figure 6-14, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[-]	*No. & proportion of hh with a dish washer*											✓	✓	Table 18, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
P92	[l]	Volume per cycle dish washer									✓				p33, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
											✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l/p/day]	*Dishwasher end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
P98	[l]	Pool volume per day [l/p/day]									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[-]	*No. & proportion of hh per sources of swimming pool water*											✓		Table 7a, Chapter 3 Water, Household Water and Energy Use Victoria [242]	2011
P99	[l]	Irrigation per day [l/p/day]									✓				Table 1-1 & p33, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l/min]	*Irrigation flow rate*									✓				Figure 4-22, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012
	[days/wk]	*Irrigation frequency*									✓				Figure 4-23, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012
	[min]	*Irrigation duration*									✓				Figure 4-21, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012
	[-]	*No. & Proportion of hh with/without irrigation systems or gardens*										✓	✓		Table 4a (state), Table 6a (state), Table 5a (SR), Chapter 3 Water, Household Water and Energy Use Victoria [242]	2011
	[-]	*No. & Proportion of hh per sources of water for each dwelling type*											✓		Table 2a, Table 3a, Chapter 3 Water, Household Water and Energy Use Victoria [242]	2011

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[-]	*No. & proportion of hh per sources of water*											✓	✓	Table 1, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
	[-]	*No. & proportion of hh per sources of water for gardening*											✓	✓	Table 8, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P100	[min]	Duration pool filtration per day														
	[hr]	*Total number of pools & duration pool filtration per day [by equivalised income quintiles and sources of water]*											✓		Table 8a, Chapter 3 Water, Household Water and Energy Use Victoria [242]	2011
P102	[-]	Number toilet flushes per person per day									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
											✓				Table 3-1, Figure 4-8, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
P103	[l]	Volume per toilet flush									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
											✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average
	[l]	*Average flush volume per type of toilet*									✓				Table 6-4, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
											✓				Table 4-6, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012/ 2010 Average
	[-]	*Half to full flush ratio per type of toilet*									✓				Table 6-5, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010
											✓				Table 3-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2012/ 2010 Average

		Parameter	Spatial scale												Data source	Temporal scale
No.	Unit	Description	HH	MB	SA1	SA2	SA3	SA4	SSC	POA	YVW	SR	State	Aus.		
	[l/p/day]	*Toilet end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[-]	*No. & proportion of hh per source of water for flushing toilets*											✓	✓	Table 9, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
	[-]	*No. & proportion of hh per type of toilet and age of dwelling*											✓	✓	Table 15, 4602.0.55.003 - Environmental Issues: Water use and Conservation [181]	2013
P105	[l]	Volume per boil														
	[l/p/day]	*Tap end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
	[l]	*Average volume per tap use event*									✓				Table 5-1, YVW (Jul 2012) Res Water Use Study – Vol 1 WINTER 2010 [115]	2010 & 2004
P106	[l/min]	Water use aircon evap. [l/operational hr]									✓				Figure 4-28 & p35/36, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012
	[l/p/day]	*Evaporative Cooler end use*									✓				Table 1-1, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012, 2010 & 2004
P107	[min]	Duration use aircon evap.														
	[hr/day]	*Duration of evaporative cooling*									✓				Figure 4-26, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012
	[day/wk]	*Frequency of evaporative cooling*									✓				Figure 4-25, YVW (Aug 2012) Res Water Use Study – Vol 2 SUMMER 2012 [116]	2012
	[-]	*Proportion of hh with aircon and aircon type*											✓	✓	Table 15, Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[months]	*Duration use aircon [no. of months]*										✓	✓		Table 7a (State), Table 8a (SR), Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
	[months]	*Duration use aircon [no. of months]*											✓	✓	Supplementary file, Table 11, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
P110	[min]	Duration use aircon rest														
	[-]	*Proportion of hh with aircon and aircon type*											✓	✓	Table 15, Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
	[months]	*Duration use aircon [no. of months]*										✓	✓		Table 7a (State), Table 8a (SR), Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
	[months]	*Duration use aircon [no. of months]*											✓	✓	Supplementary file, Table 11, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
P114	[W]	Energy used cooking														
		No. of hh with oven, proportion of energy type for oven											✓	✓	Supplementary file, Table 5, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
		No. of hh with cooktop, proportion of energy type for cooktop											✓	✓	Supplementary file, Table 6, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
P117	[W]	Energy used fridge														
		Age of fridge [per family composition or equivalised income quintile]											✓		Table 18a, 19a, 20a, 21a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
P120	[W]	Energy used TV														
		No. and Type of TV [per family composition or equivalised income]											✓		Table 23a, Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
		No. & proportion of TVs by type											✓	✓	Supplementary file, Table 20, 4602.0.55.001 - Environmental	2011

Parameter			Spatial scale												Data source	Temporal scale
No.	**Unit**	**Description**	**HH**	**MB**	**SA1**	**SA2**	**SA3**	**SA4**	**SSC**	**POA**	**YVW**	**SR**	**State**	**Aus.**		
															Issues: Energy Use and Conservation [241]	
P121	[W]	Standby energy TV														
		No. & proportion of TVs on standby											✓	✓	Supplementary file, Table 19, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
P125	[min]	Duration use PC														
		Proportion of hh with PC											✓	✓	Table 15, Table 16, Table 17, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011
P127	[W]	Standby energy PC														
		No. & proportion of PCs on standby											✓	✓	Supplementary file, Table 19, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
P128	[min]	Duration use heating														
		Duration use heating [no. of months]										✓	✓		Table 11a (State), Table 12a (SR), Chapter 1 Energy, 4602.2 Household Water and Energy Use Victoria [179]	2011
		Duration use heating [no. of months]											✓	✓	Supplementary file, Table 9, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [241]	2011
P129	[W]	Energy used heating														
		Proportion of energy type used for heating											✓	✓	Table 12, 4602.0.55.001 - Environmental Issues: Energy Use and Conservation [200]	2011

E.2. WRE Geodatabase

Table E-3: Attribute table of major water infrastructure pipes loaded into the WRE geodatabase.

Attributes	Type	Description	Example value
FID	Object ID	Unique ID Within the Database (Auto-Numbered)	0
Shape	Geometry	Major Pipe Infrastructure Layout	Polyline
CSSCLASSNA	String (50)	YVW Classification	Water-Pipe-Transfer-Main
G3E_FID	Double	--	1125082833
G3E_FNO	Double	--	519
UNIQUE_ID	Double	--	1125082834
ACTUAL_SIZ	String (20)	Pipe Diameter	375
NOMINAL_SI	Double	Pipe Diameter	375
MATERIAL	String (60)	Pipe Material	MILD STEEL CEMENT LINED
MATERIAL_A	String (20)	Abbreviated Version of Pipe Material	MSCL
SHAPE_1	String (50)	Shape of Pipe Cross-Section	CIRCULAR
CONST_DATE	Double	--	0
LINING	String (50)	--	NONE
LINING_ABB	String (2)	--	NONE
DATE_INSUL	Double	--	0
RECORD_SET	String (8)	--	M250
TRANSFER_M	String (100)	--	UNKNOWN
ROAD_NAME	String (100)	Name of Road	WANDA
ROAD_TYPE	String (30)	Type of Road	AVE
PIPE_LENGT	Double	Length of Pipe	497.458488
AMG_X_1	Double	Projected Coordinate: Pipe Start Point (Easting; WGS 1984 UTM Zone 55S)	338700.003
AMG_Y_1	Double	Projected Coordinate: Pipe Start Point (Northing; WGS 1984 UTM Zone 55S)	5800204.42
AMG_X_2	Double	Projected Coordinate: Pipe End Point (Easting; WGS 1984 UTM Zone 55S)	338773.739
AMG_Y_2	Double	Projected Coordinate: Pipe End Point (Northing; WGS 1984 UTM Zone 55S)	5800204.42
RESP_DEVEL	String (50)	--	YARRA VAL
WARRANTY	Double	--	0
FMS_FILE_R	String (50)	--	WBS673
SYS_STATE	String (9)	--	INTEGRITY
SYS_DATE_C	Double	--	20080122
SYS_DATE_L	Double	--	20110427
ASSET_OWN	String (40)	--	YV
AMG_Z_1	Double	Depth of Pipe Start Point	72.356
AMG_Z_2	Double	Depth of Pipe End Point	78.283